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Self-formation in Microelectronics

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Abstract

The external formation of integrated circuits based on lithographic processes is not the only possible method for manufacturing electron devices, either integrated circuits or photovoltaic cells. Planar technology, based on external formation, requires a certain sequence of interactions between the structured medium and the object being formed, in which the configuration of the region to be formed and its position are defined by the structure of the media and their alignment with the object. By contrast, in *self-formation* the interaction between an object to be formed and its chaotic medium is controlled by the object structure itself, and it is this interaction that changes the object's structure, leading to its increasing complexity. Three kinds of self-formation can be used in manufacturing: *self-formation*, based on a certain sequential interaction between an object and chaotic media; *development*, which requires only a single chaotic medium; and *reproduction*, which involves a developing object generating primary objects. All these cases represent self-formation of artificial systems. Simpler patterns of self-formation have already led to various patents and technologies, while more complex ones may be applied in the future. The following article attempts to define the necessary and sufficient conditions for self-formation.

Keywords: Self-Formation; Development; Reproduction; Microelectronics; Artificial Systems

1. INTRODUCTION

1.1. The concept of self-formation

The term "self-formation" defines the process of increasing complexity of artificial objects. The concept of self-formation arose from the need to describe common traits of patented manufacturing methods in microelectronic area. The term "samoformirovanije" in Russian scientific literature was introduced by the author of this article in 1974 (Janušonis, 1974). The English term "self-formation" was also introduced by the author at an international conference in Yugoslavia in 1989 (Janušonis, 1989).

The development of the theoretical principles of self-formation was motivated by the need to generalize microelectronic experience. Many processes and methods of self-formation have been verified experimentally, including by a research group led by the author.

The method of self-formation is based on topological approximation but it is limited to coplanar space, which consists of a system of parallel planes containing figures with different parameters.

The self-formation method and cellular automata have some common principles.

1.2. Technological background of self-formation

It is well known that microelectronics is based on planar technology, in which all structures are formed either in a silicon wafer surface or coated with thin dielectric and metallic films. The depth of structures in silicon wafers and the thickness of coated films are miniscule (0.01–0.1 μ). Thus, any of these layers can be approximated in terms of two-dimensional space.

The manufacture of structures occurs in specific places of a layer by surface etching, contamination, or deposition.

The shape of the structure in the layer is imparted by the transfer of its configuration from the structural medium to the layer of the object. Transference occurs through photolithography, electron—or ion—beam lithography, as well as X-ray lithography.

Nevertheless, these technological processes are accompanied by so-called parasitic effects, which have been noted

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since the onset of planar technology in 1961. Their impact has become more negative with the reduction of structure size. In 1969, these parasitic effects stimulated the search for new manufacturing methods, including self-aligning processes, which, in turn, provided the experimental background of self-formation.

Any real object can be seen as a complex of different materials arranged in a certain manner in Euclidean space. The manufacturing or development of such an object can be perceived as a rearrangement of these materials by either removing or adding new ones. The most common manufacturing methods are based on assembling an entire body from separate parts. Such methods are applied in electronics as well, in which numerous circuits can be assembled by using a limited range of components: integrated circuits, wires, resistors, capacitors, etc. This method relies on standard elements, the manufacturing of which involves many different technological processes.

An alternative method based on standard processes was applied in the manufacturing of integrated circuits. The planar process, first introduced in 1961, involves manufacturing solid-state devices and integrated circuits through the formation of regions with different types of conductivity in mono-crystalline semiconductors (germanium, silicon, and gallium arsenide). At present all these regions are produced by the insertion of donor or acceptor impurities into a wafer through its surface.

This process defines the structure of a solid-state device, which in essence is planar. The thickness of any element in the wafer is defined by the insertion process (in other words, the diffusion or ion implantation), for example, by the depth of the *p-n* junction. Dielectric and conducting elements obtain a planar character because they are produced from thin film layers.

A planar structure can be seen as a part of Euclidean space separated by two parallel planes and cylindroid surface of any configuration (Fig. 1).

The distance between two planes is determined by the processes of insertion or by the coating of thin films, whereas the configuration of a structure in a plane is created by the lithography process: photolithography, x-ray lithography, electron- or ion-beam lithography. To obtain a certain structure configuration in a homogeneous initial object, we must have a structural medium (Janušonis & Janušoniene, 1985). The medium must be of an initial configuration and interact with the object in its distinct region. As a rule, the radiation medium (light beam, electron, or ion beam X ray) is modulated in space. In this case the object generally is a radiation-sensitive layer, which is known as a photoresist.



Fig. 1. Configuration of planar structure.

Any lithography process involves a transfer of a plane figure from medium to object. This is an example of a homomorphism:

$$f : X \to X. \tag{1}$$

In this case, the configuration, number, and arrangement of figures in the object correspond adequately to the same in the medium:

$$F_t(x, y) = F_0(x, y)$$

$$n_t = n_0, \tag{2}$$

where

$F_t(x, y)$ = configuration of plane figure in object,

$F_0(x, y)$ = configuration of plane figure in medium, and

n_t, n_0 = numbers of figures on medium and object planes, respectively.

The process of transferring figures from medium to object is illustrated by Eqs. (1) and (2) and represents external formation, also known as planar technology. The time and place of this interaction between a medium and an object are regulated by human or automatic factors (Fig. 2, left).

The exposed resist regions initially are component parts of the object, but they will not comprise any part of the ultimate electron device. The resist regions merely reflect the configuration transferred from the medium, which will later define a distinct region in the wafer. Figure 3a illustrates how these processes can be carried out in which 1 represents the silicon wafer; 2, the oxide; 3, the photoresist; and 4, the exposed resist (Janušonis & Janušoniene, 1985).

The next step involves removing the exposed part of the resist by means of a developer (Fig. 3b). A window in the oxide layer is then etched through the resist window (Fig. 3c). The implantation of impurities through the oxide window can now be accomplished (Fig. 3d).

This is an example of how the interactions between chaotic media (liquid or gas) and a structured object produce a transfer of configuration from one object layer to another layer, which differs fundamentally from external formation. That is why these processes should be referred to as internal formation, which readers of patent literature will recognize as self-alignment technology (Medved & Garasi, 1969; Tatom, 1969). Internal formation adequately corresponds to Eqs. (1) and (2). The timing of the interaction is regulated by human or automatic factors, while the area of interaction is determined by the object itself.

Nevertheless, we must admit that Eqs. (1) and (2) are unable to completely approximate the subsequent processes in the structure shown in Fig. 3 because the object is three-dimensional. The oxide etching process depicted in Fig. 3 does not actually transfer vertical boundaries from the photoresist to the oxide. The points of contact between the etcher and oxide shift perpendicularly from the interface. Thus, the etching profile does not exactly correspond to a straight

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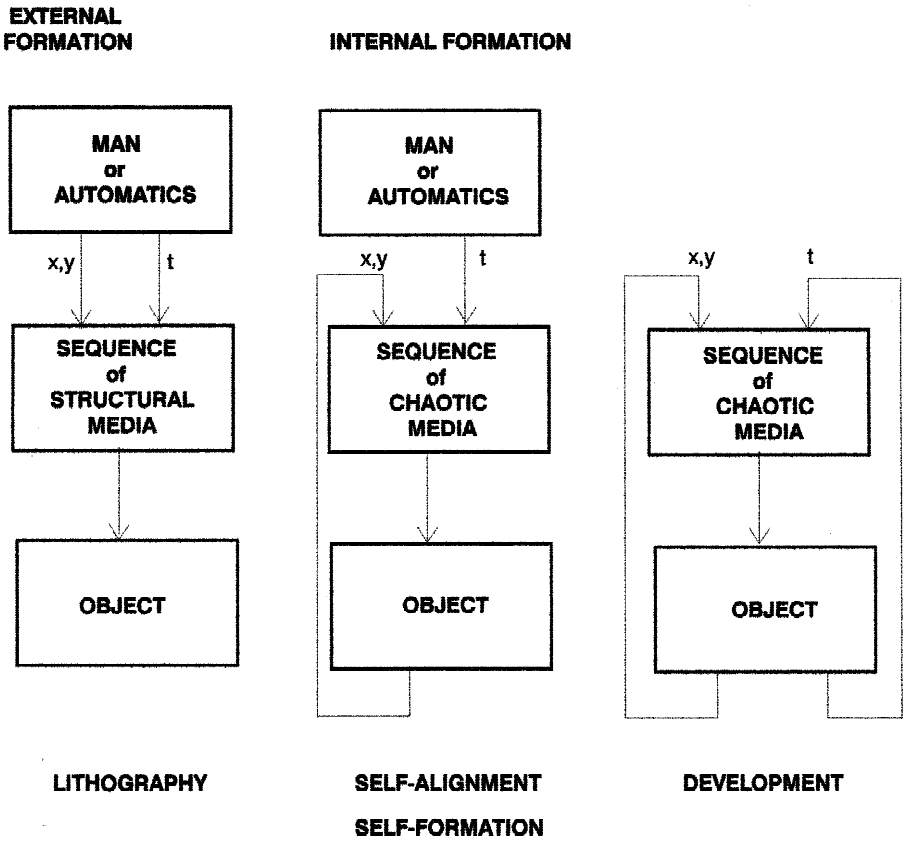


Fig. 2. Three kinds of formation of artificial objects.

line as shown in Fig. 3. Instead, it resembles a circular segment (Fig. 4a and b). If the etching continues, the plane figure begins to widen and transformation of the figure arises (Fig. 4c and d).

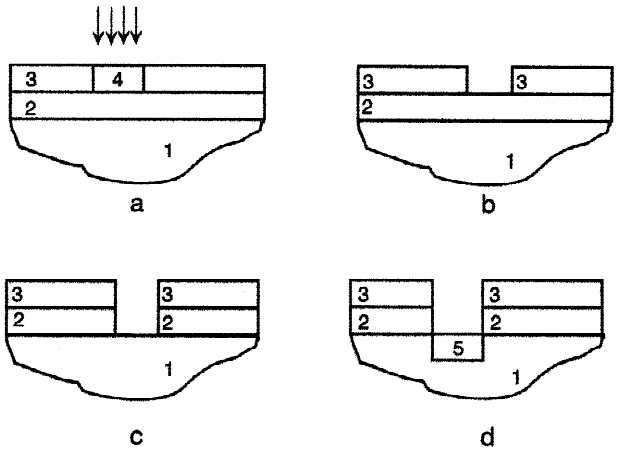


Fig. 3. Self-alignment technology; (a) structure 4 formation in layer 3 by structured medium; (b) developed structure in layer 3 by homogeneous medium; (c) structure transferred to layer 2 by homogeneous medium (etching); and (d) structure 5 transferred to wafer 1 by homogeneous medium (doping), 1—silicon wafer, 2—silicon oxide layer, 3—photoresist layer, 4—exposed resist area, and 5—doped silicon region.

Although the structure configuration changes, the number of figures remains the same.

$$F_t(x,y) \neq F_0(x,y)$$

$$n_t = n_0, \tag{3}$$

A homomorphism remains.

$$f: X \to Y,$$

$$f^{-1}: Y \to X. \tag{4}$$

We shall now consider the structure shown in Fig. 5a, in which a silicon wafer 1 is coated with an aluminium layer 2 and a mask layer 3. Assuming the structure configuration is as shown on Fig. 5b, let us oxidize aluminium in this structure. The initial structure will change, as shown in Fig. 5c and d. After oxidation in layer 2, two figures arise instead of the initial one: aluminium island 2 and oxide ring 4 (Fig. 5d).

If an initial figure were to have a more complex configuration (Fig. 6a), then oxidation could produce three figures: two aluminium islands 1 and 2 surrounded by an oxide 3 (Fig. 6b).

Thus, we observe a second case of internal formation. However, this case is rather different from self-alignment

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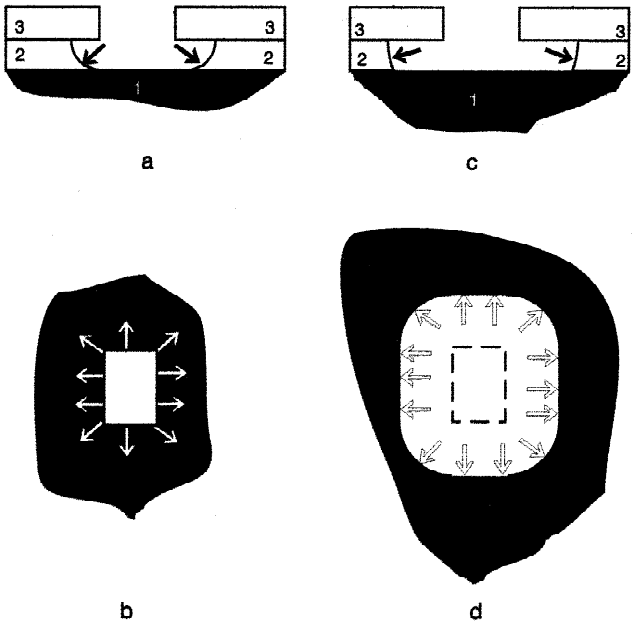


Fig. 4. Real profiles and configurations of structures in etching process: (a) Cross section of isotropically etched structure in layer 2 through hole in the mask 3; (b) top view, (c) profile of long-term etched structure; (d) profile of long term etched structure, 1—silicon wafer, 2—silicon oxide layer, and 3—photoresist layer.

because of its nonhomomorphism (Janušonis & Janušoniene, 1985):

$$f : X \to Y \tag{5}$$

$$f^{-1} : Y \to Z$$

$$F_t(x, y) \neq F_0(x, y) \tag{6}$$

$$n_t \geq n_0.$$

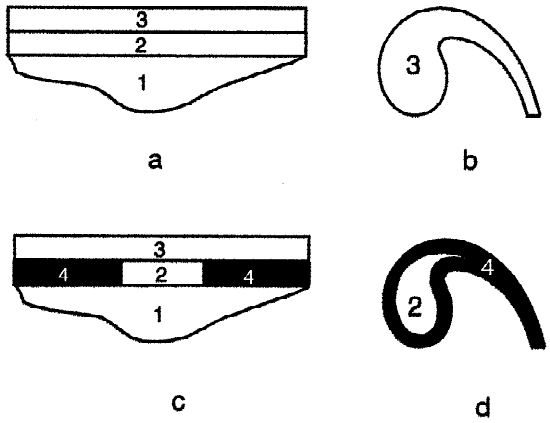


Fig. 5. Self-formation technology: (a) Cross section of initial structure; (b) top view of initial structure; (c) simplified cross section of structure after layer 2 side oxidation under masking layer 3; (d) structure top view after removing masking layer, 1—silicon wafer, 2—aluminium, 3—photoresist, and 4—aluminium oxide.

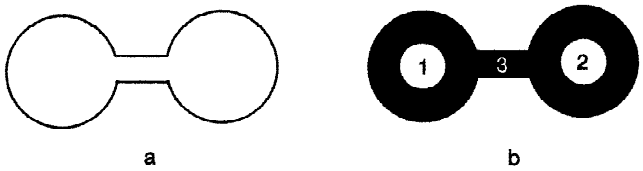


Fig. 6. More complex self-formation case: (a) top view of initial structure; (b) top view of the same structure after side oxidation; 1,2—aluminium islands, and 3—aluminium oxide.

If the interaction between a chaotic medium and structural object causes an evolution of shapes that involves changes in the number of figures, we have self-formation. It is important to note that the self-formation process can produce new figures that did not previously exist in the medium or the object.

Self-formation of single elements in electron devices is known as self-alignment. It was established that these methods are subsumed under internal- or self-formation (Janusonis, 1974). Therefore, the term self-formation is commonly used to describe internal formation, including not only self-formation per se, in which the localization in space is controlled by the object itself, and the timing is controlled by human or automatic factors (Fig. 2, middle).

In these cases, an object makes contact only with a single medium, and no external control is necessary. This situation is analogous to development and reproduction in nature (plant from a seed, bird from an egg, animal from an embryo, etc.) (Fig. 2, right).

As will become clear, necessary and sufficient conditions for such processes in artificial systems can be defined. However, the technology for either development or reproduction in microelectronics is not yet known.

APPROXIMATION OF SELF-FORMATION

Let us assume an object comprising a distinct part of Euclidean space (Fig. 7).

Let every Euclidean point of the object be juxtaposed by parameter p_i, and every point of the remaining space by parameter p_j. Assume that parameter p_i interacts with parameter p_j in such a way that parameter p_j changes to parameter p_i. We will see a broadening of the initial object.

Which mathematical methods could serve to approximate this object's evolution?

Without doubt, we can make use of classical mathematical approaches. We have a Euclidean 3D space with axis X, Y, Z, time axis t, and function $F_0(x, y, z) = 0$ approximating the object's initial surface configuration and a differential equation defining the movement course of every surface point.

In spite of this, the differential calculation is not suited to self-formation. The troubles arises in approximating any real configuration of an object, especially if it contains particu-

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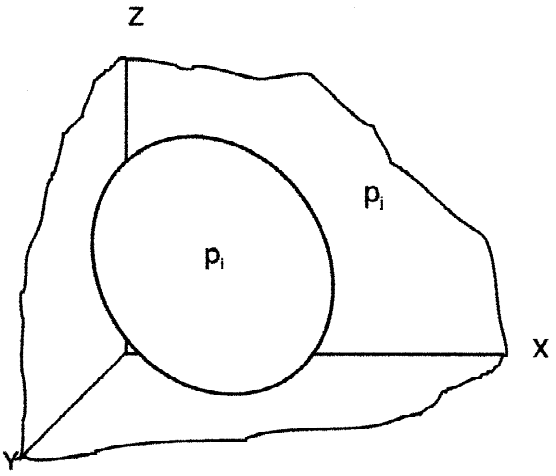


Fig. 7. An object in Euclidean space.

lar points (the points disturbing continuity of a curve). The evolutionary process permanently changes not only parameters, but also the equation itself as a set of equipotential figures. We must foresee all contacts of a surface with itself to remove some parts of a surface, or construct new object surfaces. The differential equation approach does not include causes of interaction.

Thus, we must find a method which would include causes of evolution, that is, interactions between parameters in any Euclidean point in which they come into contact. A topological apparatus was chosen as capable of satisfying all these conditions.

Let us construct a topological space representing the evolution of topological systems.

First, we must have a Euclidean space as a Cartesian product of sets *X*, *Y*, *Z* representing space axis *X*, *Y*, *Z*. Let us assume the following set:

$$\mathbb{R}^2 = (\mathbf{X} \times \mathbf{Y}) = \{(x, y) : x \in \mathbf{X}, y \in \mathbf{Y}\}. \tag{7}$$

The direct product $(\mathbf{X}\,\mathbf{Y})$ comprises a Euclidean plane and represents all combinations of (x, y). The third axis should be the *Z*-axis of the Euclidean space. But the properties of planar technology allow us to replace the **Z**-axis by a numerical set of indicators $\mathfrak{S}$:

$$\mathfrak{S} = \{(s) : s \in \mathbf{Z}\}, \tag{8}$$

in which the set $\mathfrak{S}$ as an axis of the Cartesian product is parallel to the Euclidean *Z*-axis $\mathfrak{S} \mid \mathbf{Z}$. We have a Euclidean indicated space:

$$\mathfrak{F} = \{\mathbf{R}^2 \times \mathfrak{S}\} = \{(x, y, s) : x \in \mathbf{X}, y \in \mathbf{Y}, s \in \mathfrak{S}\}. \tag{9}$$

If the set of the points *X* will be juxtaposed by the points of the set *Y* in such a way that $F_i(x, y) = 0$, the latter might represent a closed curve and we shall have a flat figure on the plane.

$$A_i = \{(x, y) \in \operatorname{Int} F_i \in R^2, i \in N\}. \tag{10}$$

The set (8) consists of the Euclidean plane points satisfying the condition $\operatorname{Int} F_i$, that is, the internal point of a figure with a boundary curve $F_i(x, y) = 0$. The points corresponding to this equation can be seen as the points juxtaposed with a certain "property." This was referred to in the introduction. However, this determination is inconvenient to use.

To simplify the task, let us introduce a set of discrete parameters in the topological space $\mathfrak{F}$ (9):

$$P = \{(p) : p \in N\}, \tag{11}$$

Then the fourth axis, the parameter set $\mathfrak{P}$, must be added:

$$\mathfrak{P} = \{(p) : p \in \mathbb{N}\}. \tag{12}$$

We have built a 4D parametrical space:

$$\begin{aligned}\mathfrak{E} &= (\mathbf{R}^2 \times \mathfrak{S} \times \mathfrak{P}) \\ &= \{(x, y, s, p) : x \in \mathbf{X}, y \in \mathbf{Y}, s \in \mathfrak{S}, p \in \mathfrak{P}\}.\end{aligned} \tag{13}$$

If the parameter *p* is correlated with a certain substance, then Eq. (11) will represent all possible substances, except that the substances will be labelled with a natural number. Therefore, the parameter *P* is the collection of all possible physical-chemical properties of a substance. The space *E* represents objects and media in the Euclidean space. This is a static space because no changes can occur in the space which does not contain the time-axis:

$$\mathfrak{T} = \{(t) : t \in \mathbb{R}\}. \tag{14}$$

We must determine the causes capable of changing the topological system in the topological space. The obvious axes $\mathbf{X}, \mathbf{Y}, \mathfrak{S}$ are fixed. On the other hand, the parameter $\mathfrak{P}$ can change in time. However, this does not mean that it is time that causes the changes. Thus the 4D space does not include the causes of evolution.

Any change in nature is caused by the interaction between an object and medium, that is, between substances. Such substances in our approximation are presented by parameters, juxtaposed by any Euclidean point. Therefore a set of interactions between two parameters can be represented as follows:

$$\mathfrak{I} = (\mathfrak{P} \times \mathfrak{P} \times \mathfrak{P} \times \mathfrak{P}) = \mathfrak{P}^4 \tag{15}$$

in which:

$$\mathfrak{J} = \mathfrak{P}^4 = \{(p_i, p_j, p_k, p_e) : i \in \mathbb{N}, j \in \mathbb{N}, k \in \mathbb{N}, e \in \mathbb{N}\}. \tag{16}$$

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The combination of parameters (p_i, p_j, p_k, p_e) implies that the change of the parameters p_i, p_j to p_k, p_e, respectively, takes place if they occur in the same neighborhood of a Euclidean point.

It is natural to select those interactions which are governed by laws of nature, and there can be an infinite set of them. Some of the well-known technological processes of planar technology are presented in Table 1.

We have 8D topological space sufficiency to approximate the evolution of all planar objects in Euclidean space, including the causes of evolution:

$$\mathfrak{L} = \{\mathbb{R}^2 \times \mathfrak{S} \times \mathfrak{P}^4 \times \mathfrak{T}) = \{(x, y, s, p, p, p, p, t) : x \in \mathbf{X}, y \in \mathbf{Y}, s \in \mathfrak{S}, p \in \mathfrak{P}, t \in \mathfrak{T}\}, \tag{17}$$

All the possible topologies with respect to $\mathfrak{J}$ in the topological space $\mathfrak{L}$ (17) are given by Eq. (18). They comprise a multidimensional matrix, which can be reduced to plane matrix columns and rows, which correspond to defined i and j, in which values of p_k and p_e maintain multivaluedness:

$$\mathfrak{J} = \begin{array}{c|cccc} & j=1 & 2 & \dots & N \\ i=1 & p_1,p_1,p_k,p_e & p_1,p_2,p_k,p_e & \cdots & p_1,p_N,p_k,p_e \\ 2 & p_2,p_1,p_k,p_e & p_2,p_2,p_k,p_e & \cdots & p_1,p_1,p_k,p_e \\ \dots & \dots & \dots & \dots & \dots \\ \mathrm{N} & p_N,p_1,p_k,p_e & p_N,p_2,p_k,p_e & \cdots & p_N,p_N,p_k,p_e \end{array} \tag{18}$$

The variables k and e can take on independent values from the sets $k \in N$ and $e \in N$ for every element in the matrix. Hence, given the set of parameters, the interaction between only two parameters $p_i p_j$ is represented by the plane matrix [Eq. (19)]:

$$\mathbf{I}p_i, p_j = \begin{array}{c|cccc} & e=1 & 2 & \dots & N \\ k=1 & p_I,p_j,p_1,p_1 & p_i,p_j,p_1,p_2 & \cdots & p_i,p_j,p_1,p_N \\ 2 & p_I,p_j,p_2,p_1 & p_i,p_j,p_2,p_2 & \cdots & p_i,p_j,p_2,p_N \\ \dots & \dots & \dots & \dots & \dots \\ \mathrm{N} & p_i,p_j,p_N,p_1 & p_i,p_j,p_N,p_2 & \cdots & p_i,p_j,p_N,p_N \end{array} \tag{19}$$

Any given combination $p_i p_j$ in the topological space can be represented by a plane matrix. Matrix (19) can be written in a simplified form:

$$p_i, p_j \rightarrow \begin{array}{cccc} p_1,p_1 & p_1,p_2 & \cdots & p_1,p_N \\ p_2,p_1 & p_2,p_2 & \cdots & p_2,p_N \\ \dots & \dots & \dots & \dots \\ p_N,p_1 & p_N,p_2 & \cdots & p_N,p_N \end{array} \tag{20}$$

Matrix (20) expresses a multivaluedness of the resulting pairs after the interaction between the parameters $p_i p_j$. However, reality admits the existence of only one element from matrix (20).

Table 1. *Technological incorporation of some of the interactions*

Interaction	Technological processes
$p_i p_j p_i p_i$	solution of layer p_j; evaporation of layer p_j; change of conductivity type on diffusion between the layers; levelling of the layers' temperature
$p_i p_j p_i p_j$	stationary state
$p_i p_j p_i p_k$	exposition of photoresist; doping by n-type impurity;
$p_i p_j p_i p_e$	analogous to $p_i p_j p_i p_k$
$p_i p_j p_i p_e$	zone clearing
$p_i p_j p_j p_j$	deposition of layer p_j: in a vacuum, on a centrifuge, electrolytical, epitaxial growth of crystal
$p_i p_j p_j p_k$	deposition of p_j glass from emulsitone, on the analogous layer p_i changing the etching rate p_i to p_j and p_j to p_k
$p_i p_j p_j p_e$	analogous to $p_i p_j p_j p_k$
$p_i p_j p_k p_i$	electrochemical coating of layer p_k which is self-detaching as a result of mechanical tension
$p_i p_j p_k p_j$	analogous to $p_i p_j p_i p_k$
$p_i p_j p_k p_k$	electrochemical oxidation, thermal oxidation
$p_i p_j p_k p_e$	diffusion with oxidation; epitaxy with diffusion; deposition with diffusion; oxide reduction
$p_i p_j p_e p_j$	analogous to $p_i p_j p_k p_i$
$p_i p_j p_e p_j$	analogous to $p_i p_j p_k p_j$
$p_i p_j p_e p_k$	analogous to $p_i p_j p_k p_e$
$p_i p_j p_e p_e$	analogous to $p_i p_j p_k p_k$

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3. ESSENCE OF 8D TOPOLOGICAL SPACE

3.1. Topological space of possibilities

Eight-dimensional topological space should be seen as a general set comprised of eight 1D infinite sets in the form of a Cartesian product:

$$\mathfrak{L} = (\mathbb{X} \times \mathbb{Y} \times \mathfrak{S} \times \mathfrak{P}^4 \times \mathfrak{T}). \quad (21)$$

The points of such a space comprise all possible combinations of eight 1D sets:

$$\mathfrak{L} = \{(x_i, y_j, \sigma_k, t_e, p_m, p_n, p_r, p_s): i, j, k, e, m, n, r, s \in \mathbb{N}. \quad (22)$$

We are able to select subsets of this general set by choosing only its distinct points:

$$\mathbf{L}_i \subset \mathfrak{L} \quad (23)$$

It is well known that the general set includes an infinite number of subsets beginning with a single point:

$$L_i = \{(x_i, y_j, \sigma_k, t_e, p_m, p_n, p_s, p_r): i, j, k, l, m, n, r = \text{const}\} \quad (24)$$

and ending with the general set itself:

$$L_g = \mathfrak{L}. \quad (25)$$

Therefore the general set represents a **topological space of possibilities**, including contradictory conditions, which provide both "yes" and "no" responses to any question.

The general set is multivalued: any interaction between two parameters can produce an infinite number of different results. The interactions occur not only between parameters juxtaposed with Euclidean points positioned in the same neighborhood but also between Euclidean points separated at any distance.

Thus, the general set can be seen as "primordial chaos," in which all manner of laws are valid, even those that are contradictory.

3.2. Evolving topological spaces

We can create any subsets from the general set. In many of them chaos will predominate. But it is also possible to create many spaces that will have an initial structure and could evolve. We might select subsets from the general set by applying some general principles. No doubt we are not limited in the choice of applied principles. However, we will base our choice on logic of the real world as a single known realization of the general set of possibilities.

We might adhere to the following principles:

1. Causality: An effect must have its cause.
2. Determination: A given cause must be followed by a corresponding result.
3. Finiteness: Interactions are of finite duration (i.e., we have a finite velocity) and occur over finite distances.

It will be shown that numerous topological spaces can be created by adhering to these principles. The number of possible topological spaces will decrease as we add new qualifications.

Eight-dimensional topological space was constructed to encompass the great number of discoveries and inventions of the technological world—including self-alignment in microelectronics technology in which new structures arise as a result of selective interaction between existing structures and a medium. No doubt it was expected that this concept of 8D topological space would disclose a multitude of new technological possibilities.

The general task of any technology may be defined as the creation of more complex objects from simpler ones. That is why we need to conceive of a topological space that will include initial structures and a set of interactions permitting an evolution of structures towards greater complexity.

Thus, the technological world requires subsets of topological space, in which an initial structure can evolve to its final determined structure. Moreover, these spaces must be optimal from the technical and economical point of view.

For this reason we are obliged to add the following additional qualifications regarding our choice of technological space.

A given point of Euclidean space can be juxtaposed with a single molecule of material; A given point of Euclidean space can be juxtaposed only by a single value of parameter p_i.

As was previously demonstrated, a set of interactions is approximated by 4D space:

$$\mathfrak{J} = (\mathfrak{P} \times \mathfrak{P} \times \mathfrak{P} \times \mathfrak{P}), \quad (26)$$

in which all possible combinations of four values of parameters are valid:

$$\mathfrak{J} = \{(p_i, p_j, p_k, p_e): i, j, k, e \in \mathbb{N}\}. \quad (27)$$

In Eq. (27) we assume that the first two parameters p_i, p_j interact in such a way that p_i becomes p_k and p_j gives rise to p_e.

Because any parameter is juxtaposed by at least one Euclidean point:

$$(x_I, y_j, \sigma_k, p_e). \quad (28)$$

Therefore, we must add a new qualification from the real world: interaction between two parameters occurs only when the distance between interacting Euclidean points is no more than would occur in reality. In other words, interaction occurs when both given Euclidean points are placed in the same neighborhood.

The choice of interaction set (interaction matrix) must be in keeping with the determination principle cited above:

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the resulting parameters must be the same in any point of time and space (although the commutative principle is not necessary).

The interactions are of a certain temporal duration and can have different velocity.

It is obvious that we must choose a topological space with a finite number of parameters, interactions, and an initial structure.

There are a great number of such topological spaces. For various purposes we may choose an appropriate topological space (a given technology).

Evolving objects

Our 8D space includes a 4D space of interactions (defined by nature):

$$\mathfrak{J} = \mathfrak{P}^4 \tag{29}$$

as well as any of its subset:

$$\mathbf{I} = \mathbf{P}^4, \tag{30}$$

which defines parameter changes occurring in the neighborhood of any Euclidean point.

The 8D topological space also includes 3D Euclidean space:

$$\mathfrak{E} = (\mathbb{X} \times \mathbb{Y} \times \mathbb{Z}). \tag{31}$$

Juxtaposing of parameters with Euclidean points constructs a 4D space, in which the position of the parameters in Euclidean space defines a spatial structure. In addition, there is a time axis. It is important to note that the Euclidean axis (31) defines the system but is not related to the evolution of an object.

The interactions (29) define the evolution of topological systems, but do not evolve themselves.

Time evolves as an independent factor and defines a situation in which a causal sequence of events can be juxtaposed with a certain increasing time value.

Thus, a topological system, consisting of a Euclidean space which includes a parameter axis, evolves as a real object:

$$\mathfrak{O} = (\mathbb{X} \times \mathbb{Y} \times \mathfrak{S} \times P) \tag{32}$$

Microelectronics devices made by planar technology may be approximated as coplanar space containing a certain number of parallel parametrical planes. Hence we have the possibility of separating interactions on a plane:

$$O_{XY} = (X \times Y \times P) \tag{33}$$

and between planes:

$$O_{\sigma} = (S \times P). \tag{34}$$

In the first case [Eq. (33)], the topological system is 3D, whereas in the second case [Eq. (34)] it has two dimensions.

Therefore, investigations of the evolution of coplanar topological systems in topological space includes:

1. The choice of interaction matrix and definition of interaction velocity.
2. The choice of the structure of the initial system. In the coplanar case we select the appropriate number of planes containing figures.

We are now in a position to make some general observations:

1. General 8D topological space may be termed the topological space of possibilities. It approximates the "primordial chaos," in which a variety of contradictory changes may occur and all possible forms of evolution could take place simultaneously. Of course the general topological space cannot exist as a whole either in real life or in the technological world.
2. We can create numerous subsets of the general set in conformity with the principles of causality, determination, and finiteness. There we have a set of evolutionary topological spaces.
3. Our real world is only one manifestation of the evolving topological spaces set.
4. Simpler subsets of real-world topological space may be used to create a technological world.
5. The initial structure and matrix of interactions determine the final result of an evolving system. In most cases, our problem is to choose an optimal structure and number of interactions.

The topological method of self-formation is similar to the cellular automata method (Toffoly & Margolus, 1991). Evolution in self-formation is analogous to the field concept. Time advances by discrete steps. Physical laws are expressed by a matrix of interactions. Every point of the boundary of a figure moves in a perpendicular direction from the boundary. Thus the laws of evolution are local and identical throughout space. However, essential differences exist between self-formation and cellular automata. The principle of cellular automata is represented *a priori* by a uniform network of cells. In self-formation the network in which evolution occurs is not given *a priori*. It is a function of the configuration of an evolving object in any time sequence, and the network causes an object to change. Hence, the cells of the network touching the boundary of the figure remain unchanging in time. It is this condition that allows us to solve in the simplest way possible a number of practical tasks in microelectronics technology.

4. SELF-FORMATION OF COPLANAR SYSTEMS IN TOPOLOGIC SPACE

The principles of self-formation can be explained by taking the bipolar transistor as an example. Let us assume a cross

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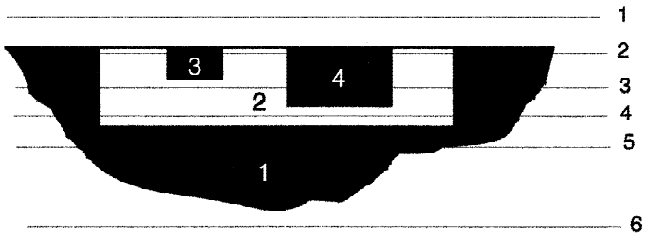


Fig. 8. Cross section of the bipolar transistor. Lines 1–6 represents the cross-secting planes, numbers 1–4 in simplified cross section of bipolar transistor—its areas.

section of a bipolar transistor (Fig. 8), which encompasses the collector region 1, the base region 2, the emitter region 3, the $p+$ base region 4.

Let us further assume that we will intersect this structure and the atmosphere as a medium with parallel planes from 1 to 6. We have a system of parallel planes containing two-dimensional figures with various configurations on the planes (Fig. 9, left).

If the physical, chemical, and other properties of every region are assigned a certain parameter value or color, we obtain a system of Euclidean planes, in which any Euclidean point is juxtaposed to a certain value of the parameter representing all properties of the transistor region. The planes may be laid out as shown in Fig. 9, right. Figure 9 represents the system at a certain point of time. Let us place the series of the sections at the following time points to the right of the initial system. This will be a schematic representation of our system involving time and space.

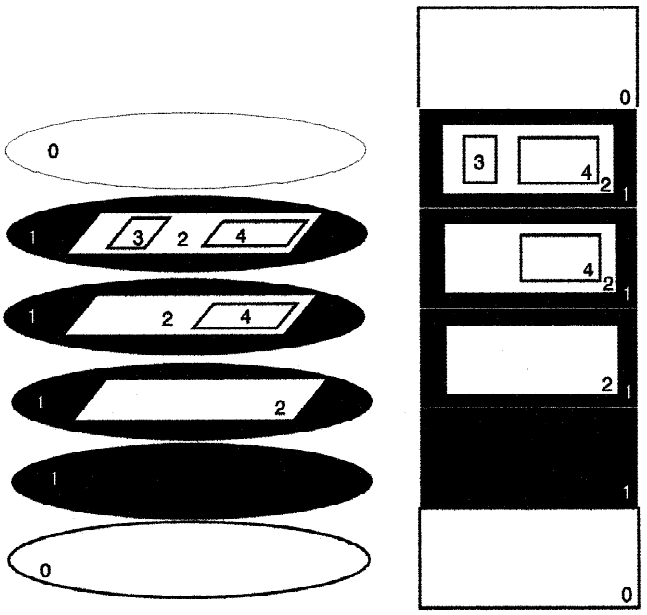


Fig. 9. Approximation of a bipolar transistor by a coplanar system: 0—atmosphere plane, 1—collector plane; 1,2—base plane; 1,2,4—p^+ base plane; and 1,3,2,4—emitter plane.

Subsequently we will investigate the evolution of topological systems as an approximation of a bipolar transistor.

Assume that the collector region of a bipolar transistor is a whole silicon wafer. We will investigate the formation of base, base p^+, and emitter regions.

Any formation of a topological system is a sequence of processes, during which a more complex system evolves from a less complex system. In most cases, we know a final system structure, that is, the number of planes as well as the configurations and parameters of figures on them. In any technology, it means that we know the structure of the object to be formed. We must choose an initial object and the sequence of technological processes. In the case of planar technology, an initial object is a homogeneous bulk known as a silicon wafer. In a topological system it is represented by one homogeneous plane with parameter p_i. Now we must transform a planar structure of an object into a coplanar topological system. Thus, we will have the topological system that will evolve. If the initial system is represented by a homogeneous plane, our problem is to find an initial structure, a sequence of media that will interact with the object during its evolution and a set of interactions sufficient to change the initial plane to a defined final plane, as shown in Fig. 10.

The same result can be attained by numerous combinations of initial structures, media planes, and interaction sets. The generation of this system has not been formalized and remains heuristic, relying on a designer's qualification and intuition. As a rule, the process is repeated to optimize the technology design.

Now it is necessary to discuss a matrix of interactions. First of all, we may have one case of interaction involving two parameters that do not interact. The resulting parameters are the same as the interacting parameters. Such interactions may be left out of the interaction matrix, but only if they never come into contact in the evolution process. As a rule, interaction occurs between parameters juxtaposed with two Euclidean points in the neighborhood of a Euclidean point. However, there are many cases in which interaction between two parametric Euclidean points exists and cases in which these points are separated by a third parameter.

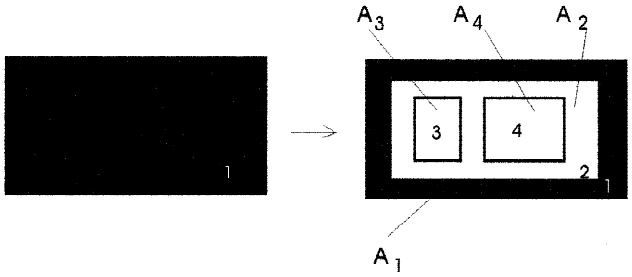


Fig. 10. Initial and final planes. Left—initial homogeneous plane with parameter 1, right—final plane with figures A_1, A_2, A_3, A_4 and their parameters 1,2,3,4.

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Thus, we have defined the distance of interaction, beyond which action stops. In this case, we have a self-completing interaction (e.g., aluminum or silicon oxidation), designated by * in an interaction matrix. Finally, the interactions may characterized by different velocities.

The elements of the interaction set can be set forth in matrix form with regard to the interacting parameters. The resulting parameters will not correlate to the rows and columns of the matrix. The interaction matrix is symmetric.

At present no operations can be carried out with a matrix. It is unclear how a structure causes evolution processes, although some principles are known. The final result can be attained in various ways. The greater the number of interactions, the simpler is the required initial object and vice versa. The greater the number of empty matrix cells, the less optimal is the choice of topological space and/or system. It is possible that the matrix defines some fundamental laws of evolution, but this has not yet been established.

No doubt we are able to choose any initial topological system and matrix of interactions for experimental reasons, as is done in cellular automata. But this multiplicity of random choices does not promote technological development because many of these choices are impractical.

In the analytical presentation a whole plane will be enclosed in brackets { }, as will a figure on the plane ( ), including its configuration and parameter. The emitter region in Fig. 10 will be denoted $(A_3,3)$. The sign "\" means "except," for example, $A_2\backslash A_3$ defines a part of figure A_2 that is not occupied by figure A_3. A homogeneous plane has only one parameter, for example, {5}.

In the case shown in Fig. 10, the initial plane evolves towards the final plane:

$$\{1\} \rightarrow \{(A_3,3)(A_4,4)(A_2\backslash A_3\backslash A_4,2)(A_1\backslash A_2,1)\}.$$

4.1. External formation of artificial systems

Let us study external formation as a schematic representation of planar technology. Suppose we have a plane system including two planes: an upper plane {0} representing the medium, and a lower one {1} representing the initial object (Fig. 11, left column).

Suppose the medium plane is changing in time according to the following sequence:

$$\{0\} \rightarrow \{(A_1,6)(\backslash A_1,5)\} \rightarrow \{(A_2,7)(\backslash A_2,5)\} \rightarrow \{(A_3,8)(\backslash A_3,5)\} \rightarrow \{0\}.$$

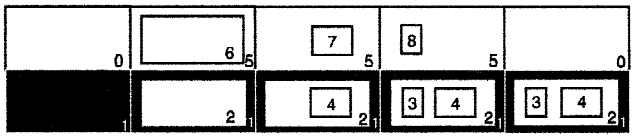


Fig. 11. External formation technology.

The set of interactions is given by the following:

0000	0101	0202	0303	0404	0505	0606	0707	0808
0101	1111	1212			1515	**1626**		
0202	2121	2222	2323	2424	2525	2626	**2747**	**2838**
0303		3232	3333		3535			3838
0404		4242		4444	4545		4747	4848
5050	5151	5252	5353	5454	5555	5656	5757	5858
6060	**6162**	6262			6565	6666	6767	6868
7070		**7274**		7474	7575	7676	7777	
8080		**8283**	8383		8585	8686		8888

The evolution will occur in the following manner:

$$\{0\}\{1\} \rightarrow \{(A_2,6)(\backslash A_2,5)\}\{1\} \rightarrow \{(A_2,6)(\backslash A_2,5)\}\{(A_2,2)(\backslash A_2,1)\}$$
$$\rightarrow \{(A_4,7)(\backslash A_4,5)\}\{(A_8,2)(\backslash A_8,1)\} \rightarrow \{(A_4,7)(\backslash A_4,5)\}$$
$$\times \{(A_4,4)(A_2\backslash A_4,2)(\backslash A_2,1)\} \rightarrow \{(A_3,8)(\backslash A_3,5)\}$$
$$\times \{(A_4,4)(A_2\backslash A_4,2)(\backslash A_2,1)\} \rightarrow \{(A_3,8)(\backslash A_3,5)\}$$
$$\times \{(A_4,4)(A_3,3)(A_2\backslash A_3\backslash A_4,2)(\backslash A_2,1)\}$$
$$\rightarrow \{0\}\{(A_4,4)(A_3,3)(A_2\backslash A_3\backslash A_4,2)\ (\backslash A_2,1)\}.$$

The medium plane {0} (i.e., atmosphere) changes into the plane with the parameter 5 and contains figure A_1 with the parameter 6 (for example, a vacuum with boron ion flow). The implantation process changes *n*-type conductivity to *p*-type, which is represented by the parameter 2. Thus, we have a base region of a transistor. Later, boron atoms will be replaced by a higher concentration of boron atoms, resulting in the p^+ region 4. The formation of the emitter region occurs in the same way by implantation of phosphorus atoms. The method presented is the most radical in external formation. The well-known planar process is based on the same principles. This process is rather universal because patterning of all regions in a semiconductor requires photomasks that differ only in their patterns. The main disadvantages of this process are associated with the necessity of producing precise masks and aligning them precisely with the object to be formed.

4.2. Self-formation of artificial systems

Let us assume that an initial system comprises an object plane $\{(A_1,2)(\backslash A_1,1)\}$ (Fig. 12, bottom) and that the medium plane varies in time according to the sequence $\{0\} \rightarrow \{3\} \rightarrow \{0\} \rightarrow \{4\} \rightarrow \{0\}$. The set of interactions is given by the matrix, in which the sign * indicates a self-completed interaction (e.g., oxidation of aluminum or silicon).

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0000	0101	0202			0505	0606	0707	0808
1010	1111		**1353**					
2020		2222	2323	2424	**2565***	2626	**2728***	2828
	3135	3232	3333		3535			
		4242		4444	4545	**4647**	4747	
5050		**5256***	5353	5454	5555	5656	5757	5858
6060		6262		**6474**	6565	6666		
7070		**7282***		7474	7575		7777	7878
8080		8282			8585		8787	8888

and the evolution occurs in the following way (Fig. 12):

$$\{0\}\{(A_1,2)(\backslash A_1,1)\} \rightarrow \{3\}\{(A_1,2)(\backslash A_1,1)\} \rightarrow \{3\}\{(A_1,2)(\backslash A_1,5)\}$$
$$\rightarrow \{0\}\{(A_2,2)(A_1\backslash A_2,6)(\backslash A_1,5)\}$$
$$\rightarrow \{4\}\{(A_2,2)(A_1\backslash A_2,6)(\backslash A_1,5)\}$$
$$\rightarrow \{4\}\{(A_2,2)(A_1\backslash A_2,7)(\backslash A_1,5)\}$$
$$\rightarrow \{0\}\{(A_2,2)(A_1\backslash A_2,7)(\backslash A_1,5)\}$$
$$\rightarrow \{0\}\{(A_2,2)(A_3,7)(A_1\backslash A_2\backslash A_3,8)(\backslash A_1,5)\}.$$

In other words, the interaction **1353** changes the parameter 1 to the parameter 5, and then the self-completed interaction **2565*** leads to the formation of the ring region around the figure A_2. Thus figure A_1 converts to figure $(A_2,2)$, figures $(A_1\backslash A_2,6)$ and $(\backslash A_1,5)$. Then we change the parameter of the medium plane 3 to the parameter 4. The interaction **4647** transforms the parameter 6 to 7, and the self-completed interaction **2728*** forms the ring region around figure A_2 with the parameter value 8, which separates figure $(A_3,7)$. Many self-formation methods permitting the manufacture of one or several structures are known (Yanushonis et al., 1978a, 1978b, 1979). The following publications (Janušonis, 1991; Janušonis et al., 1992) illustrate the only known case of the use of self-formation in manufacturing an entire field effect transistor, in which the source, drain, gate, contact regions, metallization, and isolation regions are formed.

Self-formation needs only a single photomask instead of the 5–10 in planar technology and only a single lithography process, which is the most expensive process of this technology. There is no need to manufacture a submicron precision mask, obviating the necessity of specialized equipment for either electron- or X-ray lithography. All of the media required for this process are chaotic: liquid or gaseous ambient. Self-formation technology only requires changing chaotic media.

Self-formation technology per se is the simplest case of self-formation in the general sense. But there are far more interesting examples of evolutions (Janušonis, 1992).

4.3. Development of artificial systems

The external formation of artificial systems (planar technology in microelectronics) and self-formation are not the only possible techniques for manufacturing solid-state devices and integrated circuits.

Suppose we have two object planes $\{(A_1,2)(\backslash A_1,1)\}$ and $\{3\}$ separated by a medium plane $\{0\}$ (Fig. 13). Assume the set of interactions is given by the matrix

0000	0101	0202	0303	0404	0505	0606	0707
1010	1111	1212	1313				
2020	2121	2222	**2324**	2424	**2526**	2626	2727
3030	3131	**3242**	3333	**3435***	3535		3737
4040		4242	**4353***	4444	4545	**4647***	4747
5050		**5262**	5353	5454	5555		
6060		6262		**6474***		6666	6767
7070		7272	7373	7474		7676	7777

in which the sign * indicates a self-completed interaction (e.g., electrolytic oxidation), in which the radius of interaction is expressed as $R^* > R^0$. Assume that the medium plane separating the other two object planes is removed, and that these object planes come into contact. The evolution will occur in the following manner:

$$\{(A_1,2)(\backslash A_1,1)\}\{0\}\{3\} \rightarrow \{(A_1,2)(\backslash A_1,1)\}\{3\} \rightarrow \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_1,4)(\backslash A_1,3)\} \rightarrow \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,4)(A_1\backslash A_2,5)(\backslash A_1,3)\}$$
$$\rightarrow \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,4)(A_1\backslash A_2,6)(\backslash A_1,3)\}$$
$$\rightarrow \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,4)\ (A_3,6)(A_1\backslash A_2\backslash A_3,7)(\backslash A_1,3)\}.$$

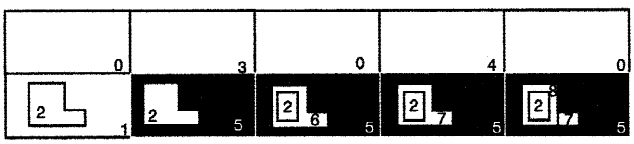


Fig. 12. Self-formation technology.

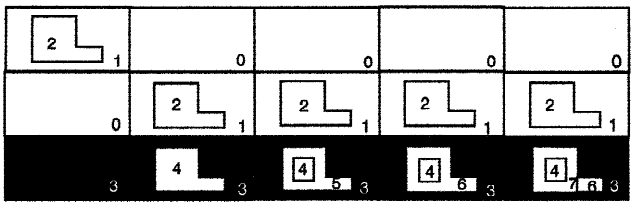


Fig. 13. Developmental technology.

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Interaction **2324** causes the formation of figure A_1 with parameter 4 in the lower plane. Then, the interaction **3435*** gives rise to the region with parameter 5. But the interaction **2526** changes the parameter 5 to 6. The latter produces interaction **4647*** and causes formation of the ring region 7.

It is important to note some interesting features of this kind of evolution. First, we have two equilibrium objects (planes). Contact between them creates a nonequilibrium object consisting of two planes, and the evolution of the structure starts. Second, no interaction between an object and medium is necessary. The complexity of the system increases without external influence.

Thus, we have an evolution analogous to the development of a living system: a plant from a seed, a bird from an egg, and an animal from an embryo. In all these cases development occurs in a single medium.

This theoretical basis allows us to create even more exotic methods of self-formation, including reproduction of artificial systems.

4.4. Reproduction of artificial systems

Assume we have two initial objects: "male" $\{(A_1,2)(\backslash A_1,1)\}\{3\}\{4\}$ and "female" $\{3\}\{4\}$ separated by the medium plane$\{0\}$, as is shown on Fig. 14.

An asymmetry of the "female" initial object with respect to the **S**-axis of the topological space allows two kinds of contact with the "male" object:

$$E_m = \{(A_1,2)(\backslash A_1,1)\}\{3\}\{4\} \text{ (male embryo)},$$
$$E_f = \{(A_1,2)(\backslash A_1,1)\}\{4\}\{3\}(\text{female embryo}).$$

Let us construct a set of interactions. In order to simplify our notation, we will show only the interactions in which at least one parameter changes, leaving out unnecessary inactive values of the parameter.

The set of interactions is given as follows:

$P^4 = \{$**1315 2326 5457 6468 8002 7001 5659* 6068 6860 9098 5750 292(10) (10)0(10)8 6(10)6(11)* (11)0(11)8 141(12) 242(13) (12)3(12)(14) (13)3(13)(14) (14)0(14) (15) (15)034 3(14)30 (12)(13)(12)(16)* 2(16)2(17) (13)(17)(13)(18)* (16)0(16)(14) (17)0(17)(14) (18) 0(18)(14) (13)0(13)(14)**$\}$.

In the case of an E_m-"male embryo," the system's evolution occurs as follows:

$$\{(A_1,2)(\backslash A_1,1)\}\{3\}\{4\}\{0\}$$
$$\to \{(A_1,2)(\backslash A_1,1)\}\{(A_1,6)(\backslash A_1,5)\}\{(A_1,8)(\backslash A_1,7)\}\{0\}$$
$$\to \{(A_1,2)\ (\backslash A_1,1)\}\{(A_1,6)(\backslash A_1,5)\}\{0\}\{(A_1,2)(\backslash A_1,1)\}$$
$$\to \ldots \to \{(A_1,2)(\backslash A_1,1)\}\{(A_2,6)(A_1\backslash A_2,9)(\backslash A_1,5)\}$$
$$\times \{(A_1,8)(\backslash A_1,7)\}\{0\} \to \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,6)(A_1\backslash A_2,10)\}\{0\}\{(A_1,2)(\backslash A_1,1)\}$$
$$\to \ldots \to \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,6)(A_3,10)(A_1\backslash A_2\backslash A_3,11)(\backslash A_1,5)\}$$
$$\times \{(A_1,8)(\backslash A_1,7)\}\{0\} \to \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,6)(A_3,10)\}\{(A_1\backslash A_2\backslash A_3,11\}\{0\}\{(A_1,2)(\backslash A_1,1)\}$$
$$\to \ldots$$

The first initial object comes into contact with the upper plane of the second initial object. The interactions **1315, 2326, 5457, 6408** cause the formation of figure A_1 in the upper and lower planes of the second object. Then the middle plane starts to develop (see Fig. 7). At the same time, the interactions **8002** and **7001** produce an initial object separated by the plane $\{0\}$. This means that these systems became autonomous. Thus, we have a new generation of the

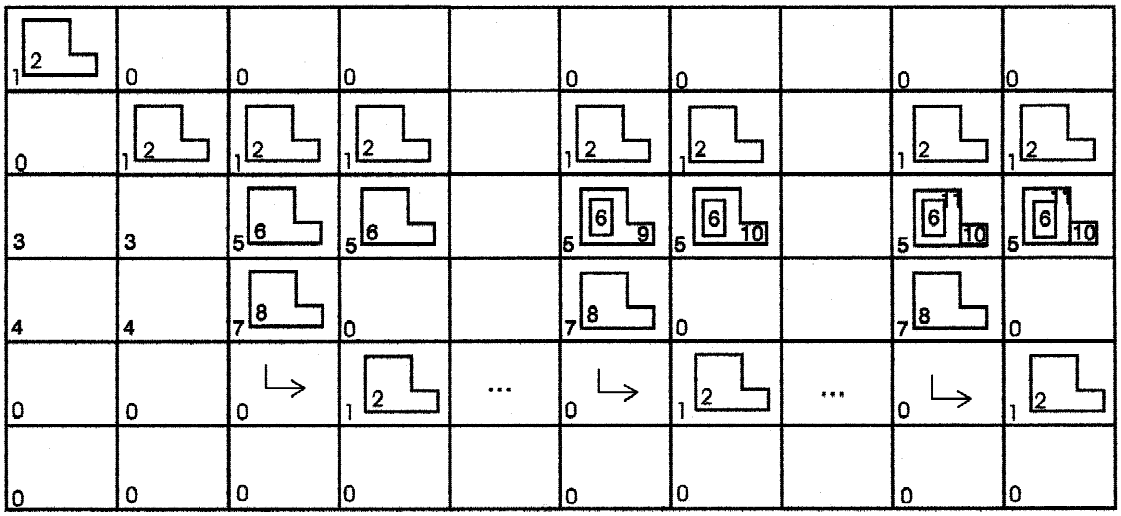


Fig. 14. Reproduction of the "male" Artificial System.

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"male" initial object. The ensuing continuous generation supports the interactions **6068**, **9098**, **(10)0(10)8**, and **(11)0(11)8**. If the primary object comes into contact with the lower plane of the "female" system, we obtain the development of the system followed by a continuous generation of the "female" initial object (Fig. 15). The following evolution takes place in this case:

$$\{(A_1,2)(\backslash A_1,1)\}\{4\}\{3\}\{0\}\{0\}$$
$$\rightarrow \{(A_1,2)(\backslash A_1,1)\}\{(A_1,13)(\backslash A_1,12)\}\{14\}\{15\}\{0\}$$
$$\rightarrow \{(A_1,2)(\backslash A_1,1)\}\{(A_1,13)(\backslash A_1,12)\}\{0\}\{3\}\{4\}$$
$$\rightarrow \ldots \rightarrow \{(A_1,2)(A_1,1)\}\{(A_2,13)(A_1\backslash A_2,16)(\backslash A_1,12)\}$$
$$\times \{14\}\{15\}\{0\} \rightarrow \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,13)(A_1\backslash A_2,17)(\backslash A_1,12)\}\{0\}\{3\}\{4\}$$
$$\rightarrow \ldots \rightarrow \{(A_1,2)\ (\backslash A_1,1)\}\{(A_2,13)(A_3,17)(A_1\backslash A_2\backslash A_3,18)\}$$
$$\times \{14\}\{15\}\{0\} \rightarrow \{(A_1,2)(\backslash A_1,1)\}$$
$$\times \{(A_2,13)(A_3,17)\ (A_1\backslash A_2\backslash A_3,18)\}\{0\}\{3\}\{4\}$$
$$\rightarrow \ldots$$

Hence there exists, at least in theory, the possibility of reproduction of even such primitive artificial systems as transistors. This reproduction bears a remarkable resemblance to the reproduction of living systems.

Two kinds of initial object are necessary and sufficient in this case. If contact with the other side of the "female" initial object is chosen, a "male" or a "female" object develops. The developing object gives rise to a generation of new "male" or "female" initial objects, respectively.

Random contact of the "male" initial object with any side of the "female" initial object gives rise to two kinds of nonequilibrium developing objects (embryos) capable of developing and generating one of the two development sequences.

CONCLUSIONS

The approximation of the technology of solid-state devices and integrated circuits by 8D topological space and the formation of objects in this topological system allow us to clarify the basic features of such formation without regard to physical processes and materials applied in different technologies.

The theory of self-formation "allows for" the existence of external formation applied in many well-known methods for manufacturing solid-state devices and integrated circuits. For the most part, these methods employ planar technology based on lithographic processes. The formation of an object, followed by its increasing complexity, is caused by its interactions with structured and chaotic media, which are controlled by man or machine.

This theory includes all known methods of self-formation technology, in which the formation of an object is driven by a sequence of its interactions with chaotic media controlled by man or machine. These methods can be applied in manufacturing submicron structures without electron-beam lithography, and they can be used when the number of lithographic processes must be reduced. The theory shows that a single lithographic process is sufficient for the self-formation technique.

The theory has pointed to new, practical methods for manufacturing solid-state devices and integrated circuits which are analogous to development and reproduction in living nature. The development can be thought of as self-formation with one lithographic and one chaotic medium. Although in theory such technology exists, its application will demand fundamental changes in our technologies and material components of electronic devices. It is conceivable that it will find application in molecular electronics, which, however, has not yet found a satisfactory means for assembling blocks from molecules.

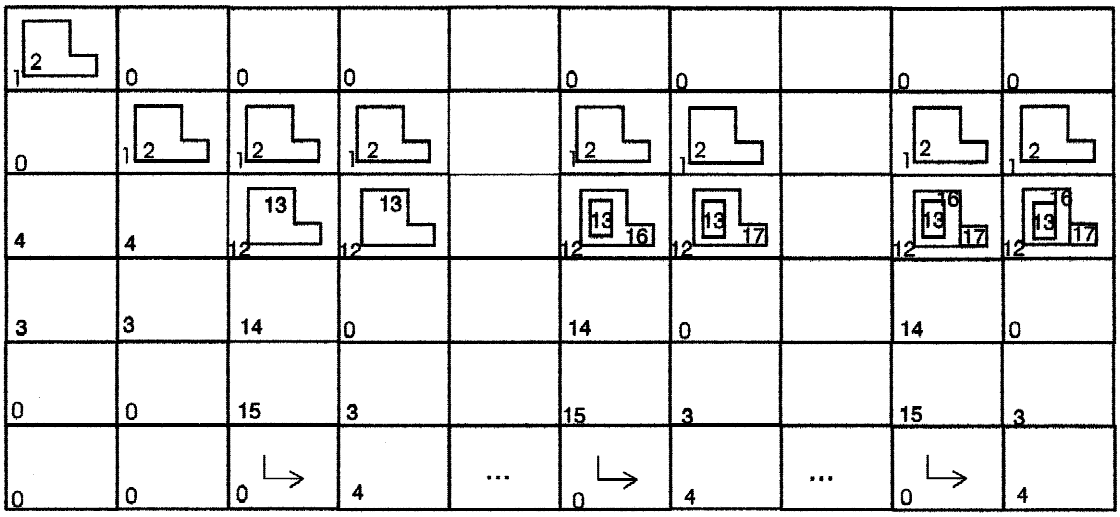


Fig. 15. Reproduction of the "female" Artificial System.

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This paper investigates only coplanar systems as approximations of well known microelectronics planar structures. However, the topological methods can also be useful in studying a significant variety of evolutions of artificial objects.

This study describes the principal possibilities of development and reproduction of topological systems which approximate bipolar transistors, thereby hopefully stimulating the search for new technological approaches.

It is important to note that the design of matrixes of interactions as well as initial structures is carried out by heuristic methods. These methods can be understand only with the help of more extensive study of interactions in the neighborhood of Euclidean points and localization in time and space, which would require another study.

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