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Semiconductor Elements Self-formation based on Qualitative Spatial Reasoning

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Introduction

In microelectronics self-formation methods can be used for generation of particular artificial objects (semiconductor elements). Self-formation simulation results are two-dimensional geometrical figures - patterns from Euclidean space. The engineer then decides which pattern is appropriate for mass production, e.g. satisfies defined conditions. The problem is to classify two-dimensional geometrical figures into two sets, two classes. Class Ω_1 describes suitable for mass production semiconductor elements structures, class Ω_2 – unsuitable.

Automation of pattern recognition can help:

- accelerate objects' selection;
- reduce work volume of designers;
- get higher class selection results.

In this case the main objects for recognition are the regions of the two-dimensional image and connections between those regions. Extraction of separate objects in the image, using special image processing techniques [9] [10], is not important in this case. The essential reasons to assign pattern to class Ω_1 are relations between the regions within the image not depending on its geometrical form.

In many cases recognition of two-dimensional pictures is based on segmentation and image smoothing techniques [11], or furthermore, using multiple classifiers, e.g. colour, shape and relational classifiers [8]. Relational classifier has been published by Cinque [12], where are two types of topological relationships between two regions, one is adjacent relationship when two regions are adjacent with each other, the other one is contained relationship when a region is contained in another region. The distance between the regions is the most important thing here. Nevertheless, colour, shape and relational classifiers uses samples to find similarities, but do not analyze structure relevancy.

The criteria for qualitative evaluation of self-formated semiconductor elements might be based on the theory of Qualitative Spatial Reasoning initially developed by Clarke [7] and further refined by many authors, including Cohn et al [4–6].

Problem

Self-formation methods to create technology for semiconductor elements (e.g. transistors, solar cells) are based on phenomenon of self-formation of artificial objects [2] [3]. Designer defines initial conditions for generating artificial objects:

- object's geometry
- number of object elements
- substances

Initial conditions influence the topology of self-formed elements. Self-formed results – semiconductor element sets – are dependent on different initial conditions. Let us suppose, that the structure of self-formed artificial object presents n substances $X = (x_1,...,x_n)$. Two different sets of elements, having different geometrical structure and different substances are presented below:

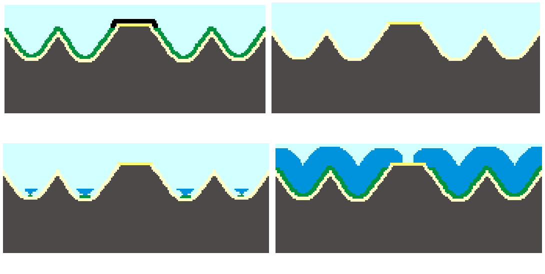


Fig. 1. Set of semiconductor elements R1

The sets of self-formed semiconductor elements are objects with different substances (regions). Only the regions and relations between the regions are important for topological semiconductor elements evaluation. The recognition of semiconductor elements (belonging to class $\Omega 1$) of any set might be done by using the same technique when substances for object generation and required object’s electrical characteristics are known. Therefore, we analyze one element of the selected set properly.

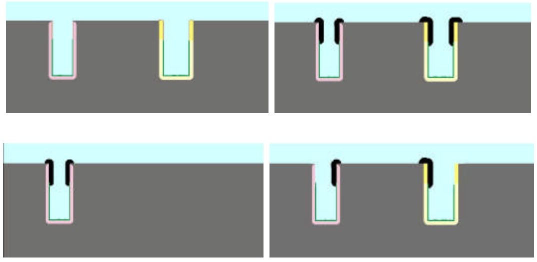


Fig. 2. Set of semiconductor elements R2

The aim of the experiment is to create reliable criteria for result classification with further use in the other experiments. For detailed analysis we choose a set of semiconductor elements R1. The set R1 represents structures of semiconductor elements with n=6 substances, X = (x_1,...,x_6), and shaped to some structure proposed by the designer. All semiconductor element substances correspond to regions X = (P, N, N+, C, D, F).

An example of artificial semiconductor element structure, having 6 substances and proposed structure, with substances notation, is given below:

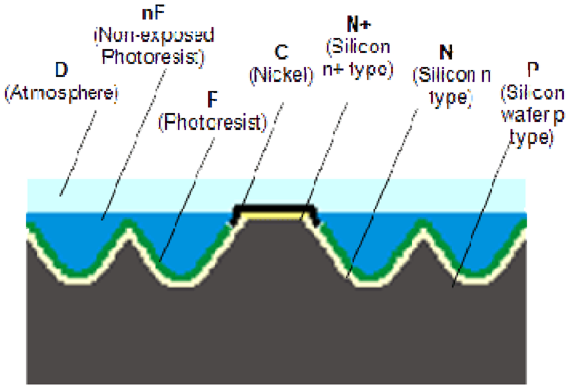


Fig. 3. Semiconductor element’s structure example

Table 1. Semiconductor element regions notation

Notation of region	Colour of region	Substance
P	Grey	Silicon wafer p type
N	Primrose yellow	Silicon n type
C	Black	Nickel
N+	Yellow	Silicon n+ type
D	Blue	Atmosphere
F	Green	Photoresist

It is necessary to decide which of the patterns have proper structure (e.g. suitable for production) and belong to class Ω_1, and which have improper structure and belonging to class Ω_2. The decision is: $X \in \Omega_s$; s = 1,2; s - ?. Obviously the evaluation can be performed by visual analysis of the generated objects.

Unfortunately, recognition of proper self-formed artificial objects (semiconductor elements) is an extremely labour consuming process. It is impossible to verify large amounts of pictures, even if we would set some limitations.

Consequently, pattern recognition can help in accelerating objects’ selection and reduce work volume in decision making process. In such case we have to define semiconductor element evaluation criteria.

Features of the semiconductor elements structure

Self-formed artificial objects structure contains n substances (regions) X = (x_1,...,x_n). Presented feature vector describes object structure belonging to class Ω_1:

$$Z_i = \begin{pmatrix} z_{i1} \\ z_{i2} \\ \cdot \\ \cdot \\ z_{ij} \end{pmatrix}; \qquad (1)$$

where $i = 1,\ldots,k;\ j = 1,\ldots,l;\ where\ k,l \in N;$ then

$$X\ (Z_i) \in \Omega_1;\ when \quad i = 1; \qquad (2)$$

$$X\ (Z_i) \in \Omega_2;\ when \quad i = 2,\ldots k. \qquad (3)$$

In order to satisfy the required electrical characteristics, semiconductor element structure from set R1 has to meet the following requirements:

$z_{1\ 1}$ - Structures must contain six different regions (P, F, N, C, N+, D),

$z_{1\ 2}$ - Regions P and C must be continuous,

$z_{1\ 3}$ - Region F cannot be continuous,

$z_{1\ 4}$ - Regions C and D are externally connected, but not overlapping,

$z_{1\ 5}$ - Regions C and N+ are externally connected, but not overlapping,

$z_{1\ 6}$ - Regions P and N are externally connected, but not overlapping,

$z_{1\ 7}$ - Regions P and N+ are externally connected, but not overlapping,

$z_{1\ 8}$ - Region D is isolated from regions P, N and N+,

$z_{1\ 9}$ - Structures must not contain any other regions (4)

More substances can participate in the process of self-formation of semiconductor elements, but they will not appear in the ultimate result.

The results of self-formation simulation of semiconductor elements are two dimensional geometrical figures from Euclidean space. The criteria for qualitative evaluation of such results are based on the theory of Qualitative Spatial Reasoning, the separate formalism – RCC (Regional connection calculus), initially developed by Clarke [7] and further refined by many authors, including *Cohn, Randell, Cui, Bennett* [4,5,6].

RCC theoretical background for evaluation criteria

The fundamental approach of RCC is that extended spatial entities, i.e. regions of space, are primary rather than the traditional mathematical dimensionless point. The primitive relation between relations is that of connection, thus giving the language the ability to represent the structure of spatial entities [4].

Qualitative Spatial Reasoning theory is used for GIS, image analysis, etc. This theory is also called C theory, as from ‘Connectivity’, and characterized by essential axioms. All arguments to predicates below are named regions. In such interpretation[1], the regions may be of arbitrary dimensions, provided they are all of the same dimensions. The regions cannot be null, but they may be multiple regions or contain holes.

The basis of the system is one primitive dyadic relation **C(x,y)** read as “*x connects with y*”.

The essential axioms are as following:

1. $\forall x[C(x,x)]$ (reflexivity); (5)
2. $\forall x \forall y\ [C(x,y) \rightarrow C(y,x)]$ (symmetry) ; (6)
3. $NC(x,y) \equiv_{def} \neg C(x,y)$ (regions *x* and *y* disconnected); (7)
4. $EC(x,y) \equiv_{def} C(x,y) \wedge \neg O(x,y)$ (region *x* is connected with region *y*); (8)
5. $O(x,y) \equiv_{def} \exists z[P(z,x) \wedge P(z,y)]$ (regions *x* and *y* overlaps) ; (9)
6. $P(x,y) \equiv_{def} \forall z[C(x,z) \rightarrow C(z,y)]$ (region *x* is a part of *y* region); (10)
7. $EQ(x,y) \equiv_{def} P(x,y) \wedge P(y,x)$ (regions *x* and *y* are equal); (11)
8. $CON(x) \equiv_{def} \forall yz[EQ(sum(y,z) = x \rightarrow C(y,z)]$ (self-connected region). (12)

Graphical interpretation of axioms illustrated in Fig. 4.

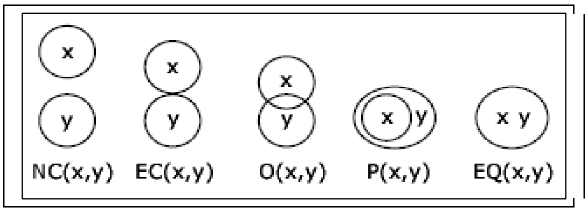
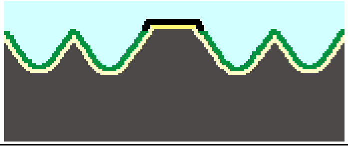
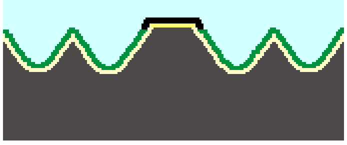
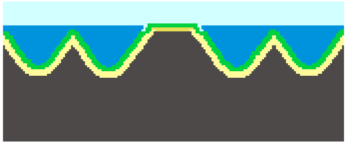
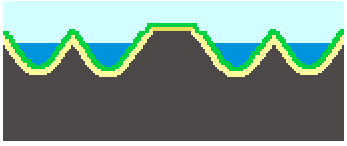
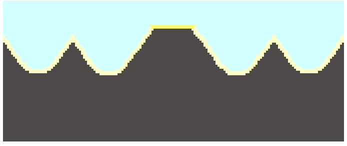
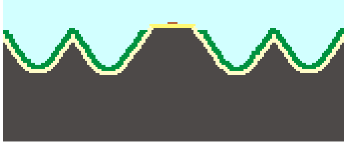


Fig. 4. Essential RCC axioms

Depending on the RCC axioms and requirements for semiconductor elements of structure (4), let us describe results which shows that semiconductor element X = (P, N, N+, C, D, F) belongs to class Ω_1 :

$$CON(1,P) \wedge CON(1,C) \wedge CON(0,F) \wedge EC(C,D) \wedge EC(C,N+) \wedge EC(P,N) \wedge EC(P,N+) \wedge NC(D,P) \wedge NC(D,N+) \wedge NC(D,N) \wedge \exists(P,F,N,C,N+,D)\ . \quad (13)$$

Table 2. Semiconductor elements dependence to class Ω_1 and Ω_2 having different feature vectors

$X(Z_i) \in \Omega_1,\ i=1$	
X	Z_i
	Z_1
	Z_1
$X(Z_i) \in \Omega_2,\ i=2,..l$	
X	Z_i
	Z_2
	Z_2
	Z_3
	Z_4

According to RCC axioms and requirements for semiconductor elements of structure (4), we note that semiconductor element X = (P, N, N+, C, D, F) belongs to class Ω_2 if meets following condition:

$$\neg CON(1,P) \vee \neg CON(1,C) \vee \neg CON(0,F) \vee \neg EC(C,D) \vee \neg EC(C,N+) \vee \neg EC(P,N) \vee \neg EC(P,N+) \vee \neg NC(D,P) \vee \neg NC(D,N+) \vee \neg NC(D,N) \vee \neg\exists(P,F,N,C,N+,D)\,, \quad (14)$$

where CON (1,P) – Region P must be continuous; CON (0,F) – Region F cannot be continuous; EC(P,N) – Regions P and N are externally connected; NC (D,P) – Regions P and D are not connected.

In case when n=6 and X = (P, N, N+, C, D, F), object belongs to class Ω_1 ($X \in \Omega_1$) unless and until all conditions of feature vector Z_1 are met:

$$Z_1 = \left(\begin{array}{c} z_{11} = \exists(\mathrm{P, F, N, C, N+, D}) \\ z_{12} = CON(1,P) \\ z_{13} = CON(1,C) \\ z_{14} = CON(0,F) \\ z_{15} = EC(C,D) \\ z_{16} = EC(C,N+) \\ z_{17} = EC(P,N) \\ z_{18} = EC(P,N+) \\ z_{19} = NC(D,P) \\ z_{110} = NC(D,N+) \\ z_{111} = NC(D,N) \end{array} \right). \tag{15}$$

The results from the set R1 can be classified by using the generated criteria, based on RCC technique. The criteria can be refined if needed and be used on the other sets of self-formed semiconductor elements if the initial conditions are known.

In Table 2 the following notations are used:

$$Z_2 = \left(\begin{array}{c} z_{21} = \exists(\mathrm{P, F, N, N+, D, Fn}) \\ z_{22} = CON(1,P) \\ z_{23} = CON(0,F) \\ z_{24} = EC(P,N) \\ z_{25} = EC(P,N+) \\ z_{26} = NC(D,P) \\ z_{27} = NC(D,N+) \\ z_{28} = NC(D,N) \end{array} \right); \tag{16}$$

$$Z_3 = \left(\begin{array}{c} z_{31} = \exists(\mathrm{P, N, N+, D}) \\ z_{32} = CON(1,P) \\ z_{33} = EC(P,N) \\ z_{34} = EC(P,N+) \\ z_{35} = NC(D,P) \end{array} \right); \tag{17}$$

$$Z_4 = \left(\begin{array}{c} z_{41} = \exists(\mathrm{P, F, N, N+, D, R}) \\ z_{42} = CON(1,P) \\ z_{43} = CON(0,F) \\ z_{44} = EC(P,N) \\ z_{45} = EC(P,N+) \\ z_{46} = NC(D,P) \\ z_{47} = NC(D,N) \end{array} \right). \tag{18}$$

Proposed recognizer approach

Automation of self-formed artificial object classification can help to accelerate objects' selection and reduce work volume in decision making process. The idea of software application (e.g. recognizer) is described below. The main task for recognizer is to analyze generated patterns – semiconductor elements - by using proposed criteria, classify them and output results.

Operation sequences of the recognizer:

- Get object (pattern)
  - Create RGB array for every pixel
- Set point labels
  - Create RGB values - labels table
  - Create point value array
- Initialize rules
  - Read RCC rules from file
- Check rules
  - Initialize objects' regions array where region label (e.g. point label) and region number is in array
  - Find connections between regions
  - Test all RCC rules for the object
- Print results

At first system reads the object – two-dimensional image, and then creates an array where elements consist of RGB values of the pixels, image width and image height. Thus, depending on RGB values, the system initializes image point's array where elements are labels. System assigns image to class Ω_2 immediately if none of described RGB labels are found.

Table 3. RGB values - labels

Label	Substance	*R*	*G*	*B*
101	P	77	73	72
103	N	255	251	156
150	C	0	0	0
105	N+	229	222	86
0	D	210	255	255
140	F	0	210	63

```
∃           101
∃           103
∃           150
∃           105
∃            0
∃           140
CON          1          101
CON          1          150
CON          0          140
EC          150          0
EC          150         105
EC          101         103
EC          101         105
NC           0          101
NC           0          105
NC           0          103
```

Fig. 5. Content of the RCC rules file

The second step is to read RCC rules, corresponding to Z_1 feature vector (15). These rules will be applied for every image region as well (Fig. 5).

System initializes regions while analyzing elements of the point's labels array of read image. Every region is marked with point label value and has an 'id' (integer value). It is necessary when two or more same colour regions are found within the image. This process also includes finding connections between regions. In other words, system identifies all region connections.

The example of regions array is given below:

Regions = {0,1}, {140,2}, {150,3}, {140,4}, {105,5}, {103,6}, {105,7}, {101,8};

Regions-neighbors array:

RegionsNeighbors = {{0,1}, {140,150}}, {{140,2}, {0,150,103}}, {{150,3}, {0,140,105,103}}, {{140,4}, {0,150,103}}, {{105,5}, {140,150,105,101}}, {{103,6}, {150,103,101}}, {{105,7}, {140,150,105,101}},{{101,8}, {105,103}};

Conclusions

- Self-formatted structure evaluation based on semiconductor topology criteria where described.
- The idea of semiconductor element recognition based on regional connection calculus rules - the separate formalism of qualitative spatial reasoning, was presented.
- Reliable criteria for semiconductor elements classification with presumptive further use in structure recognition of various self-formed semiconductor element sets were proposed.
- Pattern recognition theory, methods and computerized tools open new way of:
- reducing design volume of work of self-formed artificial objects
- accelerating design process of artificial objects
- reaching higher selection quality of artificial objects

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Automated engineering technologies (e.g. self-formation) for manufacturing of electron devices are widely popular in microelectronics. Topological approach allows for analysis and synthesis of such real world object structures: transistors, solar cells. The analysis of such object structures in order to meet defined electrical characteristics becomes an actual problem since it is an extremely labour consuming process. Automatic recognition of self-formed semiconductor elements, which can speed up the analysis process, is discussed in this paper. The idea of using qualitative spatial formalisms for analysis of semiconductor element structures is presented. Reliable criteria for semiconductor elements classification with presumptive further use in structure recognition of various self-formed semiconductor element sets were proposed. Ill. 5, bibl. 14 (in English; summaries in English, Russian and Lithuanian).

Д. Саулевичюс, Л. Леонас. Качественный анализ структур самоформирующихся полупроводниковых элементов // Электроника и электротехника. – Каунас: Технология, 2009. – № 1(89). – С. 15–20.

Автоматизированные инженерные технологии (например, самоформирование) производства электронных устройств широко популярны в микроэлектронике. Топологический подход позволяет проводить анализ и синтез транзисторов и солнечных ячеек. Анализ структур таких объектов, которые имеют определенные электрические особенности становится фактической проблемой, так как это чрезвычайно долгий и трудный процесс. Автоматическое опознавание самосформированных элементов полупроводников может ускорить процесс анализа. В данной работе представлена идея использования качественного пространственного формализма для анализа структур элементов полупроводников. Предложенные критерии для классификации элементов полупроводников могут использоваться в будущем для опознавания структур различных наборов самосформированных полупроводниковых структур. Ил. 5, библ. 14 (на английском языке; рефераты на английском, русском и литовском яз.).

D. Saulevičius, L. Leonas. Savaimingai besiformuojančių puslaidininkinių elementų kokybinė struktūros analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 1(89). – P. 15–20.

Pastaruoju metu elektronikos pramonėje, integruotų schemų gamyboje plinta naujos savaiminio formavimosi technologijos. Šių elementų struktūrų topologinė analizė įgalina atlikti tokių objektų sintezę ir analizę. Aktuali masinės tokių objektų gamybos problema tampa jų struktūrų tinkamumo tam tikroms charakteristikoms tenkinti analizė. Šiame darbe aptariamas dirbtinų savaiminio formavimosi puslaidininkinių elementų atpažinimas. Pristatoma idėja, kaip naudoti kokybinės struktūros analizės teorijos formalizmus puslaidininkinių elementų struktūroms atpažinti. Pasiūlytas metodas gali būti naudojamas įvairiems saivaimingo formavimosi puslaidininkinių elementų rinkinių struktūroms atpažinti. Il. 5, bibl. 14 (anglų kalba, santraukos anglų, rusų ir lietuvių k.).