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Optimization of the 3D-IC model structure

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Abstract. This article describes an algorithm of optimizing the placement of the main constituent elements of 3-D integrated VLSI circuits. To solve the formulated problem of optimization, it is proposed to use a modified genetic algorithm. The proposed algorithms, models and methods have been implemented in the software. The article presents the structural scheme and the results of the developed software.

1. Introduction

The 3-D integrated circuit (3D-IC) is a multi-layer object within which non-stationary physical processes occur [1, 11]. Given the high degree of integration, the problem of heat distribution within 3D-IC is very important [2, 5].

In designing 3-D integrated VLSI, the developer can choose arrangement of the crystals and arrangement of IP blocks on the chip area. Obviously, close arrangement of highly heated elements will result in appearance of local overheat areas, which, in turn, adversely affect operation of the entire device [8]. Numerous components make the task of finding the optimal arrangement highly non-trivial, therefore developers of 3D-ICs have the need for special software tools that can automate the arrangement process.

In changing the geometric structure of the object, it is important to consider possible restrictions on arranging layers or elements in the layer. For example, an element or layer may be fixed, or should take a certain coordinates range.

The presence of various, hard to formalize and conflicting limitations, availability of various optimization criteria allow attributing the problem of 3D-IC components arrangement to complex problems of optimization [4, 5].

2. Formulation of the optimization task

The optimization task is divided into two subtasks:

1) Obtaining a set of variants of heated elements arrangement inside the selected layers (layer structure optimization);

2) Obtaining a set of variants of arrangements of the selected layers themselves with regard to the obtained results of layer structure optimization.

Let us reduce the problem of arranging the elements in the layer to the well-known problem of arranging rectangles in a plane. The initial data of the problem are the number and the size of elements, as well as their thermal characteristics. The criterion for assessing quality of arrangement is aimed at the uniformity of distribution of heat sources.

Let us denote the area of possible elements arrangement as D. The area of this zone $S_D= w_D h_D$, where w_D and h_D are the layer dimensions. Let's take n for the number of arranged elements and denote the set of arranged elements (rectangles) as $E= \{e_1, .., e_n\}$. Each arranged element $e_i \in E$ is characterized by three parameters: its length (w_i), width (h_i) and the maximum heating power (p_i). The solution of the problem is vector $ke=(ke_1, ke_2, .., ke_n)$. Here $ke_i=(x_i, y_i, \alpha_i)$ specifies location of the e_i item, i.e. the coordinates of its center (x_i and y_i) and the rotation angle (α_i). The internal structure of element ei is considered uniform, so α may be determined by a one-bit variable that specifies (or does not specify) pi rotation by 90^o.

In solving the problem of arrangement, the following limitations are to be observed (1) – (5).

The area of possible arrangement cannot be less than the total area of the atrranged elements:

$$\sum_{i=1}^{n} S(e_i) \le S(D) \tag{1}$$

The area of possible arrangement should include all arranged elements:

$$e_i \in D,\ \ i = \overline{1,n} \tag{2}$$

The elements should not overlap:

$$e_i \cap e_j = \varnothing,\ \ i \ne j;\ \ i,j = \overline{1,n} \tag{3}$$

Arrangement of the element may be anchored:

$$k_{ei} = const \tag{4}$$

The coordinates of the anchor point may be limited to the specified range:

$$x_i \in [x_i^{min}; x_i^{max}],\ \ y_j \in [y_i^{min}; y_i^{max}] \tag{5}$$

Thus, the arranged elements may be divided into three groups:

1. anchored (the coordinates of the anchor points are determined and cannot be changed);
2. freely positioned (the area of arrangement is limited only to area D);
3. conditionally freely positioned (indication of intervals of possible changing anchor points coordinates in the coordinate axes).

The function of assessing mutual arrangement of two elements e_i and e_j (with $p_i>0$ and $p_j>0$) looks as follows:

$$f(k_{ei}, k_{ej}) = l_{i,j}^2 / p_i p_j = ((x_i - x_j)^2 + (y_i - y_j)^2) / p_i p_j \tag{6}$$

Where $l_{i,j}$ is the distance between the centers of the elements e_i and e_j in vector k_e.

The task of optimizing arrangement may be described as follows: in view of the constraints (1-5), one has to find such a vector $\overline{k}_e$, with which

$$F(\overline{k}_e) = \max\left\{ \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} f(k_{ei}, k_{ej}) \right\} \tag{7}$$

After obtaining one or more variants of the optimum arrangement of elements inside the layers, arrangement of the layers is to be optimized.

The solution to optimization of layers arrangement problem will be vector $\overline{k}^L=(k^L_1, k^L_2,.., k^L_N)$. Here $k^L_i=(n^L_i, \alpha^L_i, q_i)$, n^L_i is the number of layer l_i, α^L_i is rotation of layer l_i, and q_i is the number of the variant of elements arrangement within layer l_i. At the same time, α^L_i can be one of the four values indicating the rotation of the layer by 0, 90, 180 and 270 degrees.

For any vector $\overline{k}^L$, the following constraints are introduced (8)-(10).

The sequence number of layers should not coincide:

$$n_i^L \neq n_j^L, i = \overline{1,N}, j = \overline{1,N}, i \neq j \tag{8}$$

The sequence numbers of layers should not exceed the total number of layers:

$$n_i^L \leq L, i = \overline{1,N} \tag{9}$$

Layer location may be anchored:

$$k_i^L = const \tag{10}$$

The number of layers is taken as N. A set of layers is denoted as $L=\{l_1,l_2,..,l_N\}$.

To estimate thermal parameters of the object, a three-dimensional matrix P with dimensions N×m×n is introduced. Each element p_{kij} of matrix P characterizes the power of the heat source located on layer l_k with coordinates i, j. If there is no heat source with these coordinates, then $p_{kij}= 0$.

The goal of optimizing layers arrangement is ensuring uniform distribution of heat sources inside a multilayer object for reducing the probability of occurrence of local zones of overheating. In other words, the more powerful two heat sources are, the farther from each other they should be located. Based on this, the function quality assessment for some arrangement k^L is defined as

$$F(\bar{k}^L) = \min\left\{ \sum_{k_1=1}^{N} \sum_{i_1=1}^{n} \sum_{j_1=1}^{m} \sum_{k_2=k_1}^{N} \sum_{i_2=i_1}^{n} \sum_{j_2=j_1}^{m} (p_{k_1 i_1 j_1} \cdot p_{k_1 i_1 j_1} / r^2) \right\} \tag{11}$$

Where $p_{k_1 i_1 j_1}$ and $p_{k_1 i_1 j_1}$ are powers of heat sources with coordinates $k_1 i_1 j_1$ and $k_2 i_2 j_2$, and $r = \sqrt{(k_1-k_2)^2+(i_1-i_2)^2+(j_1-j_2)^2}$ is the distance between them.

Equation (11) assesses the impact of all elements in matrix P on each other. This requires large resources of the computing system, in case of using (11) as the target function when the genetic algorithm is used, since the target function is calculated with each iteration of the cycle (see Fig. 2). For a flat multilayer object, the influence of the elements in matrix P is assessed separately for each column P. The quality of heat sources arrangement inside a column of matrix P with coordinates x, y is assessed with equation

$$f_{column}(x, y) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (p_{ixy} \cdot p_{jxy} /(i-j)^2) \tag{12}$$

The modified target function for genetic algorithm of optimizing arrangement of layers is as follows:

$$F_{column}(\bar{k}^L) = \min\left\{ \sum_{i=1}^{n} \sum_{j=1}^{m} f_{column}(i,j) \right\} \tag{13}$$

3. The use of the modified genetic algorithm

Adaptation of the genetic algorithm (GA) to the problem of layers arrangement is in defining the following parameters:

1. the method of population coding;
2. the method of forming a population;
3. implementation of genetic operators of selection, recombination and mutation;
4. presentation of the target function for assessing the proposed variant of arrangement;
5. forming the shutdown criteria; and
6. the optimum values of changed parameters of the genetic algorithm.

The genetic algorithm of optimizing the arrangement of elements on the layer is shown as a diagram in Figure 1. The project information is represented by binary coding. The coding chromosome (CCH) is a string, in which information about each arranged element is represented in the binary code: the coordinates of the anchor point and the element rotation angle. In this method of presentation, the length of CCH is determined by formula:

$$L = N(\log_2 w_d + \log_2 h_d + 2), \quad (14)$$

where N is the number of elements; w_d h_d is the length and width of arrangement area D.

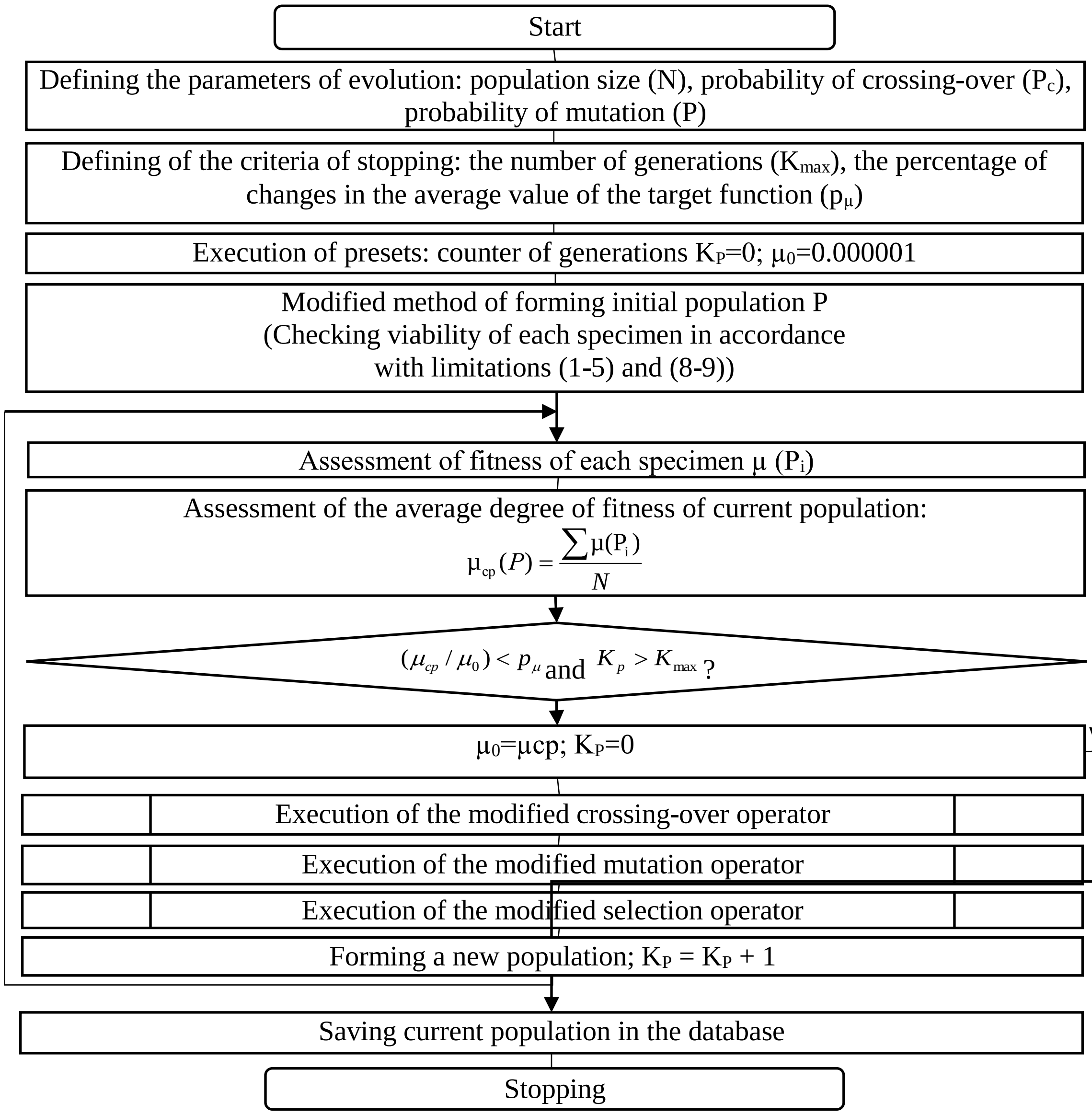

Figure 1. Diagram of GA for optimization of arrangement of 3D-IC elements

Modification of genetic operators is aimed at minimizing the risk of looping the algorithm in the area of the local extremum of the target function.

4. The software implementation of the proposed optimization algorithm

The software modules for optimizing arrangement of elements within the layer and optimizing arrangement of layers have a similar structure shown in Figure 2.

The graphical user interface of the system for optimizing arrangement of heating elements contains information about the simulated object, selected layer, and arranged elements. Here GA parameters are adjusted, and the limitations for arrangement of the selected element are set. The status of operation, errors, and other information are displayed in the console. The results of optimization can be displayed as a diagram of changes in the TF, and in text form.

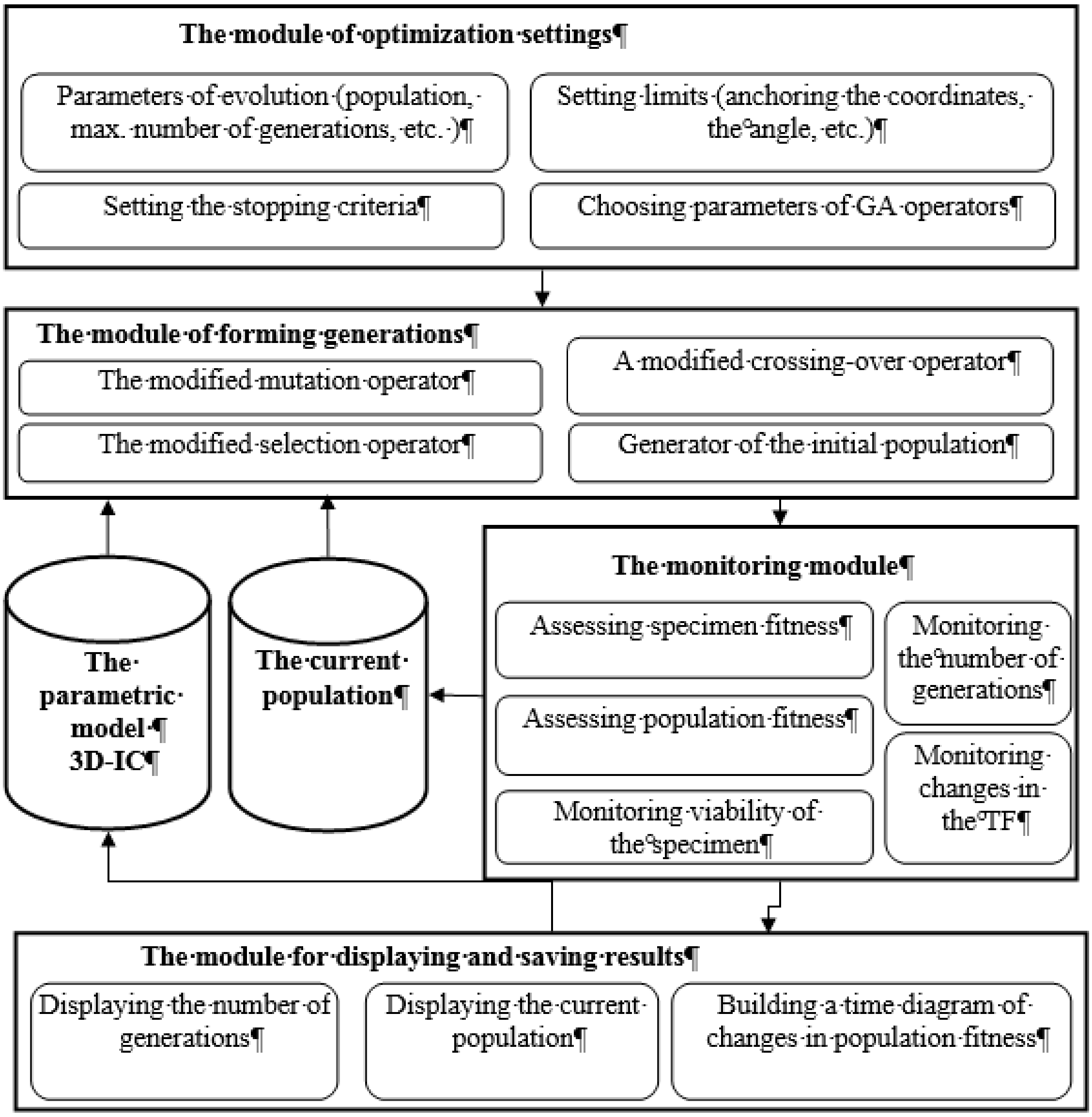

Figure 2. Block diagram of the GA-based optimization module

The graphical user interface of the system for optimizing arrangement of the layers contains information about the simulated object: the object name, the quantity and size of layers, etc. Here GA parameters are adjusted, and the limitations for arrangement of the selected layer are set. The status of operation, errors, and other information are displayed in the console. The results of optimization can be displayed as a diagram of changes in the TF, and in text form.

5. The results of the proposed software

To check correct operation of the application, an existing model of an 8-bit microcontroller was used. The freely arranged and conditionally free elements are schematically presented in Figure 3. The dimensions of the elements are indicated in the brackets.

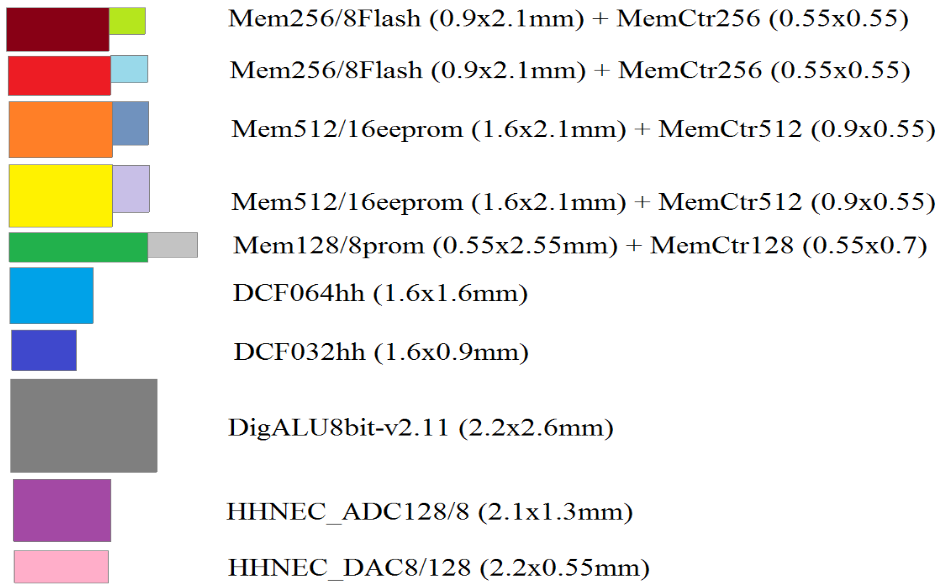

Figure 3. The freely arranged elements of the modeled object

Memory elements (Mem256/8Flash, Mem512/16eeprom, Mem128/8prom) and elements of control (MemCtr128, MemCtr256, MemCtr512) are rigidly attached to each other, i.e. they are conditionally free. Elements DCF064hh, DCF032hh, DigALU8bit-v2.11, HHNEC_ADC128/8 and HHNEC_DAC8/128 are freely arranged.

The area of arrangement, i.e. the space of the crystal with anchored elements is shown in Figure 4.

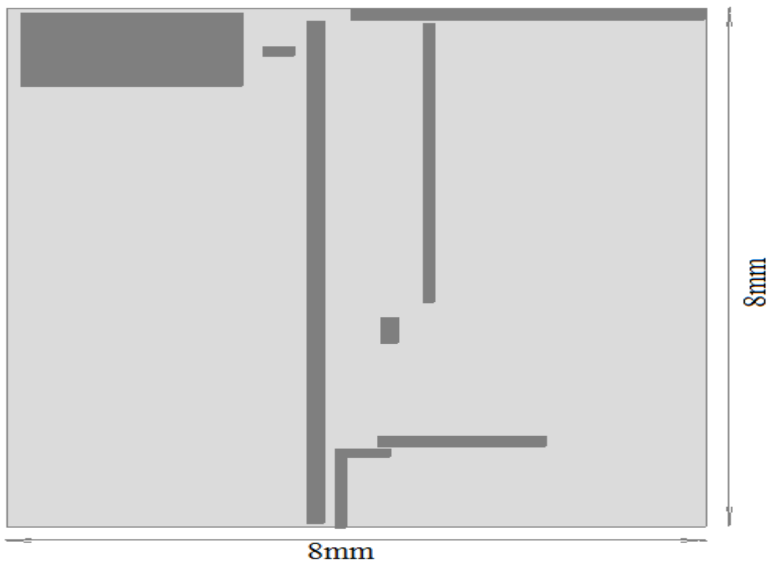

Figure 4. The area of arrangement with anchored elements.

As a result of studying the model with the use of the approximate method based on the modified genetic algorithm, 10 possible options of arrangement were identified, 3 of which have been rejected for technical reasons. After building and analyzing thermal models, the final variant of arrangement has been chosen, which is schematically shown in Figure 5. The selected variant coincided with the arrangement obtained with the use of the Cadence Design Systems software and implemented on the chip (see Figure 6).

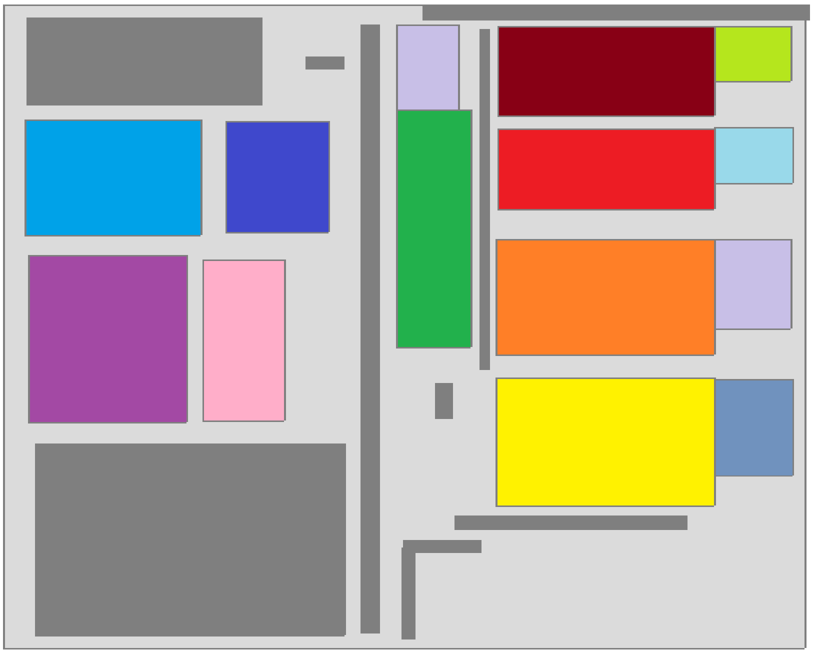

Figure 5. The final way of elements arrangement

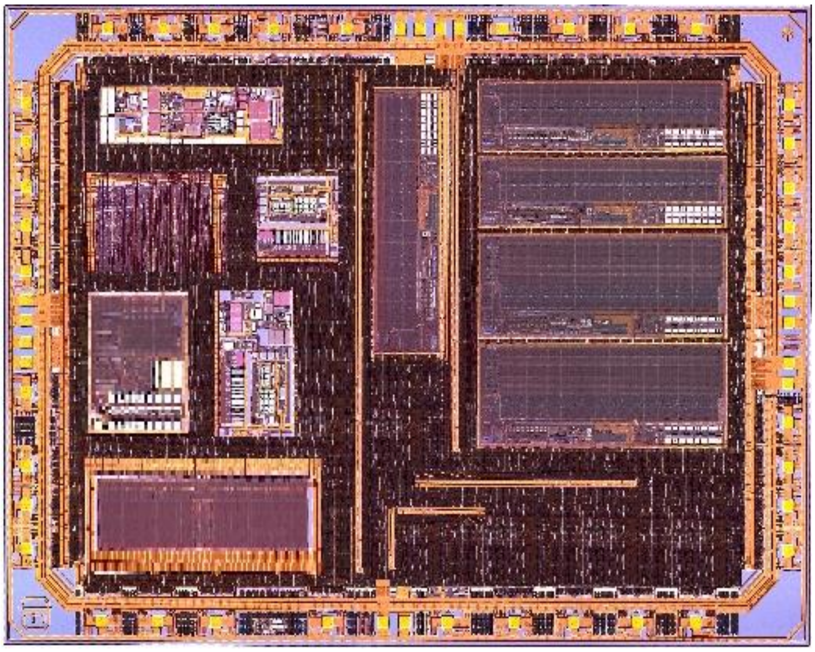

Figure 6. The variant of arrangement obtained in the Cadence software

6. Conclusion

The proposed software module is part of the software suite for modeling thermal distribution inside multilayer objects [6, 7]. Simulation of thermal distribution with the use of the developed software suite, and comparison of the results with the data obtained by a thermal imager were also performed for a number of other semiconductor devices. Analysis of the results obtained with with the use of software suite showed good adequacy of generated models [3, 9]. The performed experiments confirm the working efficiency of the modules included into the developed software suite, and, as a consequence, correctness of theoretical calculations.

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