Computer Simulation of the Response of a Semiconductor Wafer with a Self-Affine Pattern in the Form of a System of Coupled Ring Grooves to Electromagnetic Radiation

Gennadi Lukyanov, Alexander Kopyltsov, and Igor Serov

Abstract We simulated the response of a surface with a circular relief on a semiconductor wafer constructed using self-affine transformations to the effect of an incident electromagnetic wave. The study assumed that the main mechanism leading to the reaction of the plate to incident radiation is electric polarization, which, for example, is the basis for the functioning of a number of electronic components, such as a MOS FET or a CCD. Since silicon belongs to polarizable materials, a spatial separation of charges occurs in a changing electric field in the volume of a silicon crystal in accordance with the law of change of field. If a silicon wafer is used, on one of the surfaces of which a certain relief is created, then the distribution of charges under the relief will be uneven in space in accordance with the pattern of this relief.

Keywords Regular self-affine microrelief · Ring-shaped grooves · Electric field · Computer simulation · Wave structure

1 Introduction

Regular microrelief surfaces have been used for a long time. These include, for example, diffraction gratings. Widely used are devices on surfactants, the basis of which is also a regular surface relief. Now there is a study of new areas of application of devices with a regular microrelief on the surface. For example, there are studies [1] where the effect of thermal radiation from such heated surfaces is investigated. It was shown [1] that in the near field this radiation has spatial coherence.

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In our study, we present an object that also has the properties of self-similarity and scale invariance, but so far it is not widely represented in the studies. It is obtained in the process of scaling and rotation of the circle taken as a basis and further transformations of the aggregates thus obtained [2].

An affine transformation of a vector whose origin coincides with the origin and the end has coordinates (x_1, y_1), into a vector whose origin is at a point with coordinates (b_1, b_2), and the end at a point with coordinates (x_2, y_2) has the form [3]:

$$\begin{cases} x_2 = a_{11}x_1 + a_{12}y_1 + b_1 \\ y_2 = a_{21}x_1 + a_{22}y_1 + b_2 \end{cases} \tag{1}$$

\System (1) can be represented in the form of the matrix:

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & b_1 \\ a_{21} & a_{22} & b_2 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} \tag{2}$$

and to illustrate by Fig. 1.

Also, using affine transformations, you can assign the operation of rotation through the angle α.

$$T_1 = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \end{bmatrix} \tag{3}$$

and scaling.

$$T_2 = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \end{bmatrix} \tag{4}$$

For $m > 1$, the distance from the origin occurs; for $m < 1$, it approaches the origin. With an increase or decrease in the scale of the figure by a factor of m, an increase or decrease in its size by a factor of m occurs.

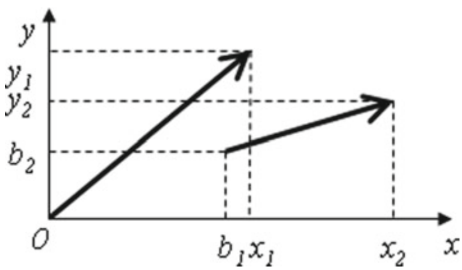


Fig. 1 Affine transformations of the vector

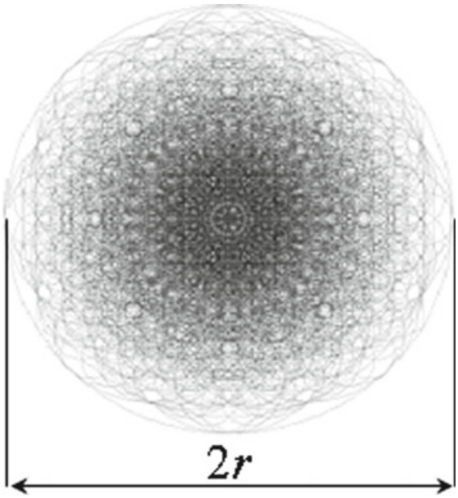


Fig. 2 The LIFETUNE resonator

2 Object of Study

The behavior of a silicon wafer was studied, on the surface of which a pattern of a large number of ring-shaped grooves was etched by plasma-chemical etching (see Fig. 2). The studied object, the LIFETUNE resonator, is a silicon wafer on the surface of which there are annular grooves 0.2 μm wide and 0.8 μm deep, the pattern of which obeys the laws of self-similarity and scale invariance, and is based on affine transformations that is, this surface is self-affine by construction [2].

This figure was obtained as a result of the implementation of affine transformations, the initial stages of which are illustrated in Fig. 3.

3 Experiment

We considered the interaction of an electromagnetic wave with a plate surface for a non-stationary case, for a two-dimensional model. A change in the distribution of tension with time over the surface of the resonator was simulated for various boundary conditions.

An electric field interacting with a semiconductor causes a charge displacement phenomenon and, due to the fact that the plate has a smaller thickness in the "groove" region, the concentration of charge carriers in the groove region will be higher than in neighboring regions. Then most of the charge carriers are concentrated in the regions under the grooves (see Fig. 4).

Let the charge density of two adjacent grooves be q_1 and q_2, respectively, and the potentials φ_1 and φ_2 (see Fig. 5).

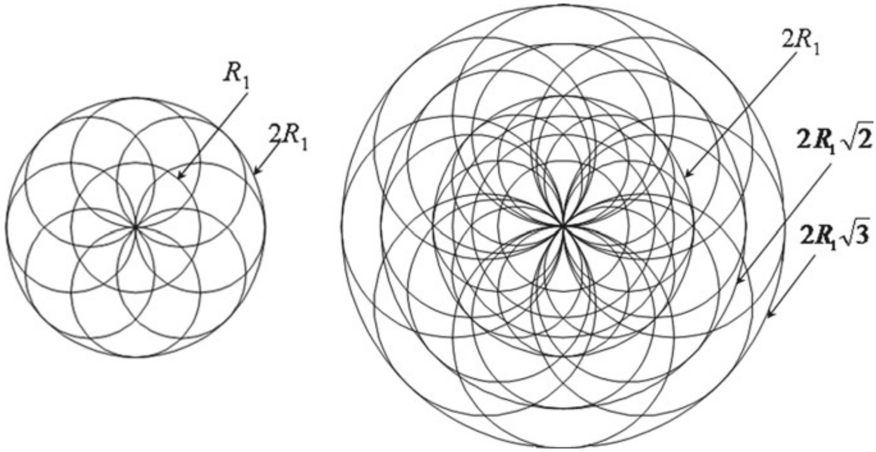


Fig. 3 Create a self-affine relief

Fig. 4 The charges

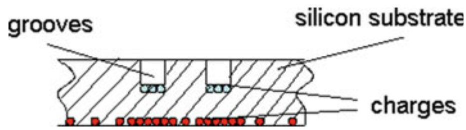
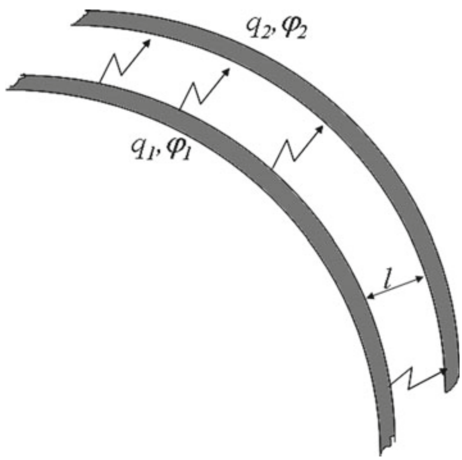


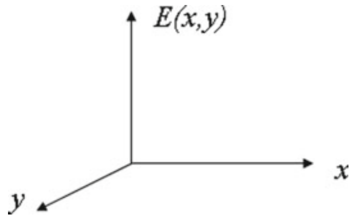
Fig. 5 The potentials φ_1 and φ_2



When the potential reaches some critical value φ_c, a current arises along the shortest distance between the grooves. The induced electric field strength E_{ind} then has the form $E_{ind} = (\varphi_1 - \varphi_2)/l$.

The mathematical model for this case has the form:

Fig. 6 The distribution of E (x, y) over resonator in plane (x, y)



$$\frac{\partial E}{\partial t} = \alpha_1\left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2}\right) - \frac{E}{\alpha_2}. \tag{5}$$

where: E—electric field strength, t—time; α_1, α_2 are the coefficients, x, y are the coordinates. In the simulation, it was assumed that the law of current change when the potential reaches the value $i = 1 - (e^{-\beta t}\cos(\omega_0 t))$.

The condition at the cavity boundary: $E = 0$ for $r > \sqrt{x^2 + y^2}$. In the last expression, r is the radius of the resonator (Fig. 2). In addition, the results were compared with the sink in the center of the cavity ($E = 0$) and without it, when the value of E in the center is obtained as a result of calculation by model (5).

4 Results and Discussion

The simulation results in the form of the distribution of the value of E (x, y) (see Fig. 6) are shown in Fig. 7. Since model (5) is dynamic, the figures show different stages of the process at different times, in which waves of different lengths and orientations are visible.

The sizes of the plate along the x and y axes are 20×20 mm. Waves with different lengths and orientations arise due to the complex structure of the resonator surface, which creates an "orchestra" of interconnected wave processes.

5 Conclusions

Regardless of the conditions at the surface boundary, after some time t_s, a stable multi-frequency distribution of the electric field strength over the resonator surface is established.

The surface under consideration acts as a transducer of the radiation incident on it and gives a response in the form of a set of waves. When the period of incident electromagnetic radiation changes, the distribution of the electric field on the surface retains its character.

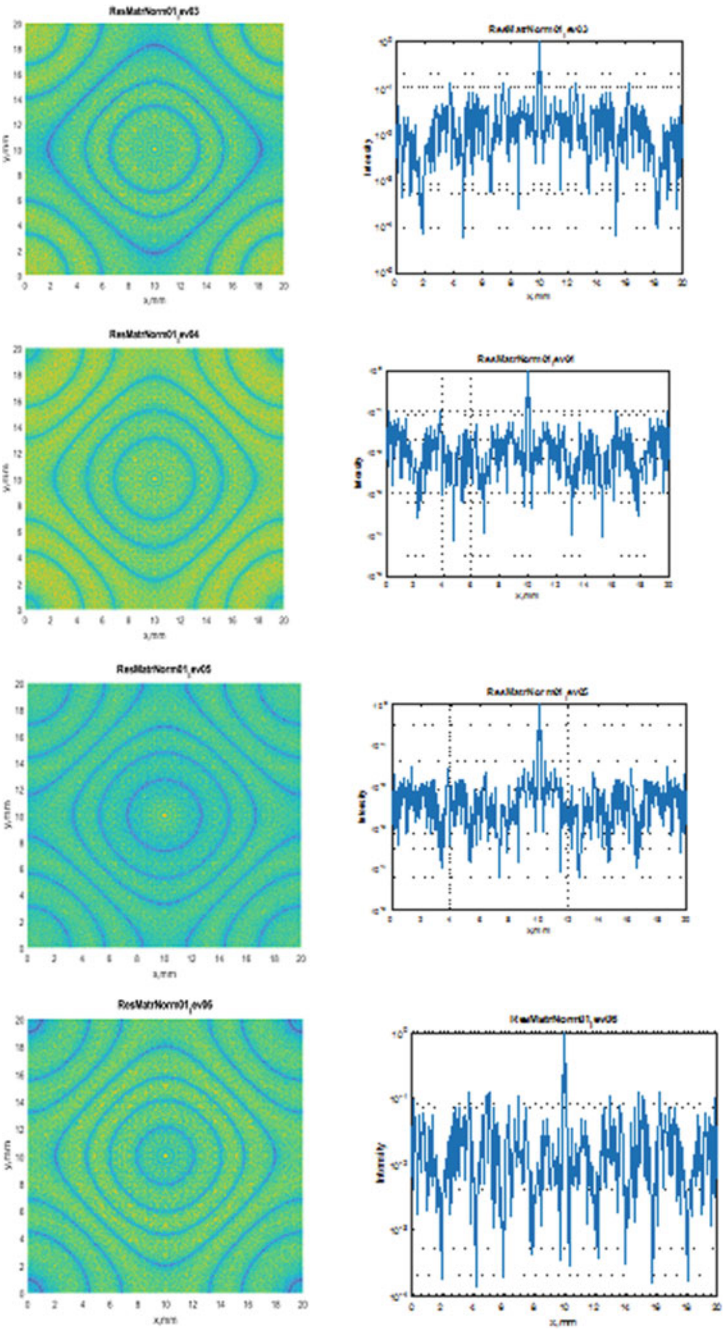


Fig. 7 *E* (*x*, *y*). Change over time

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