

Experimental study of the behavior of a silicon wafer with self-affine surface relief during periodic heating and cooling

GENNADI LUKYANOV, SERGEI MAKAROV
Faculty of Control Systems and Robotics
ITMO University
Kronverksky Pr. 49, bldg. A, St. Petersburg, 197101
RUSSIA
gen-lukjanow@yandex.ru <http://www.ifmo.ru>

Abstract

The paper considers periodic heating and cooling of a silicon wafer with a self-affine ring relief of grooves on the surface. Its temperature field is measured. These measurements demonstrate that such a wafer has a high emissivity factor in the relief region, which is significantly higher than in the regions of the same wafer where there is no relief. This is due to the fact that during heating, the apparent temperature values in the relief region are significantly higher than in the neighboring regions. The results of the measurements and conclusions from them are presented.

Keywords

Self-Affine Microrelief, Heating-Cooling, Temperature, Absorption

1. Introduction

Devices with a surface having a regular relief constructed according to a certain law have been known for a long time. Such devices are widely used, for example, in optics. These are Fresnel lenses, diffraction gratings, interference filters, etc., the action of which is based on the laws of optics, such as refraction, reflection, transmission of light. In the works (Kopyl'tsov, Lukyanov, 2007, 2022) we considered the modeling and simulation of the behavior of a silicon wafer with a self-affine relief of circular grooves on the surface. The assumption was used as a model that when such a wafer is exposed to an electric field, it behaves like such devices as, for example, MOS transistors (MOS-FET), the principle of which is based on the ability of semiconductors in an electric field to transition from an electrically neutral state to an electrically charged one. The basis for this is electrical polarization - the emergence of free charges in an electric field. The configuration of the grooves results in the concentration of electric charges on the surface of the plate becoming uneven: the charges gravitate towards the areas where the grooves are located. Since the concentration of electric charges in a semiconductor strongly depends on temperature, it is interesting to see how such a surface formed on a semiconductor plate behaves when the temperature changes.

The temperature dependence of semiconductors poses a serious challenge for both analog integrated circuit designers and their users. In these devices, sensitivity to temperature changes leads to so-called temperature drift. This phenomenon causes the output voltage to shift despite a constant or zero input signal. On the other hand, semiconductor temperature sensors are widely used due to their very high sensitivity to temperature changes. Therefore, it was interesting to study the behavior of an object such as a wafer with a self-affine ring pattern on its surface under the influence of a temperature field. If a temperature field configuration is created that causes free electrons to shift from the smooth surface of the wafer to a plane with a self-affine relief, it can be assumed that the electron concentration near the relief surface should also be non-uniform. To test this hypothesis, the experiment described in the article was designed and conducted.

For this experiment, periodic heating using a Peltier battery was applied. The reaction of the plate surface was recorded using a thermal imaging device. The temperature field of the surface was measured.

2. Object

The object of the study is a silicon plate with ring grooves that form a pattern that obeys the laws of self-similarity and scaling.. The manufacturer calls it “Lifetune”. This is a square silicon wafer measuring 20 mm x 20 mm x 1 mm, on the surface of which there are ring grooves (width 0.2 μm and depth 0.8 μm) the arrangement of which obeys the laws of self-similarity and scale invariance and is based on affine transformations (see Fig.1). This surface is self-affine by construction (Kopyltsov, Lukyanov, 2007). It has previously been shown that when exposed to an electric field, this device responds with a multi-frequency response, in which the frequencies are determined by the self-affine structure of the surface. This multi-frequency resonance occurs, which is why we call it a "resonator."

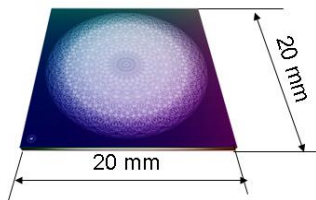


Fig. 1 Appearance of the object of the study (resonator)

This figure was obtained as a result of the implementation of affine transformations, the initial stages of which are illustrated in Fig. 2 a and b, and the final result of the transformations in Fig. 2 c.

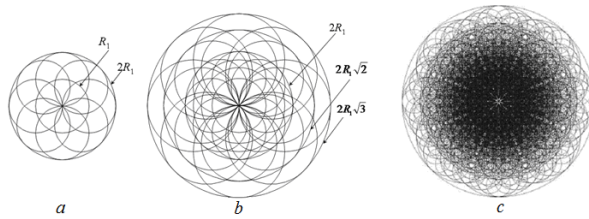


Fig. 2. First stages of the construction of the self-affine surface.

In our previous works (Kopyltsov, Lukyanov, 2007, 2022), we considered the modeling and simulation of the behavior of a silicon wafer with a self-affine relief of circular grooves on the surface (Kopyltsov, Lukyanov, 2007), and we considered the interaction of an electromagnetic wave with the surface of the wafer. The change in the distribution of electric field over time on the surface of resonator was modeled. The electric field interacting with the 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. Therefore, it was assumed that most of the charge carriers are concentrated in the regions under the grooves (see Fig. 3).

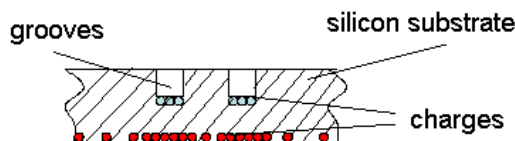


Fig. 3. The charges.

Let the charge density of two neighboring grooves be q_1 and q_2 , respectively, and the potentials φ_1 and φ_2 (Fig. 4).

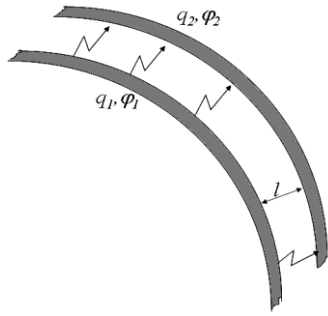


Fig. 4. The potentials φ_1 and φ_2 . Potentials and currents between grooves that arise when the potentials exceed a critical value

When the potential reaches a certain critical value φ_c , a current arises along the shortest distance between the grooves. Based on these assumptions, a numerical simulation of the process of interaction of an electromagnetic wave with the surface of a plate was performed. This surface configuration results in the structure responding to different influences with the same pattern of electric field on the surface. For this reason, we will further call this object a “resonator”.

3. Experiments with heating and cooling

In these experiments, the resonator was periodically heated down and cooled up using a Peltier battery. This experimental setup is shown in the photos Fig. 5.

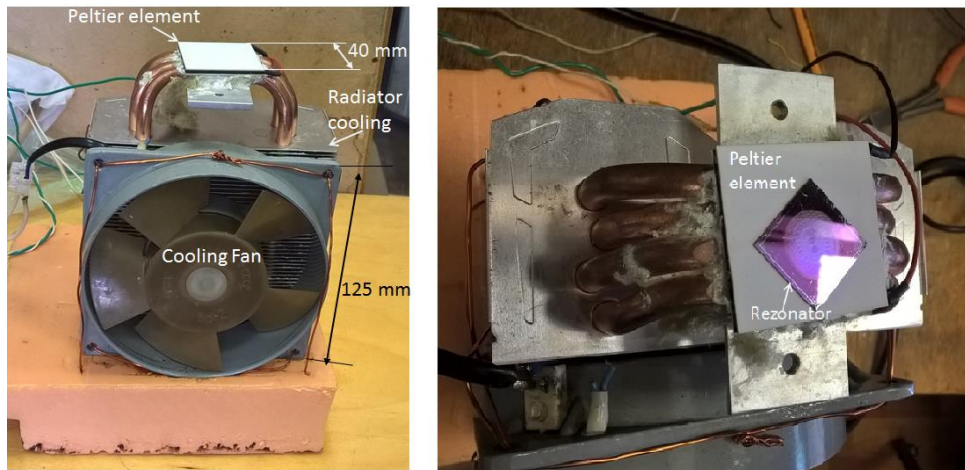


Fig. 5. . Peltier battery

Heating and cooling of the Peltier element were carried out by switching the direction of the current through it. The current polarity switching circuit is shown in the Fig. 6. At one polarity of the current the resonator was cooled, at the other – heated.

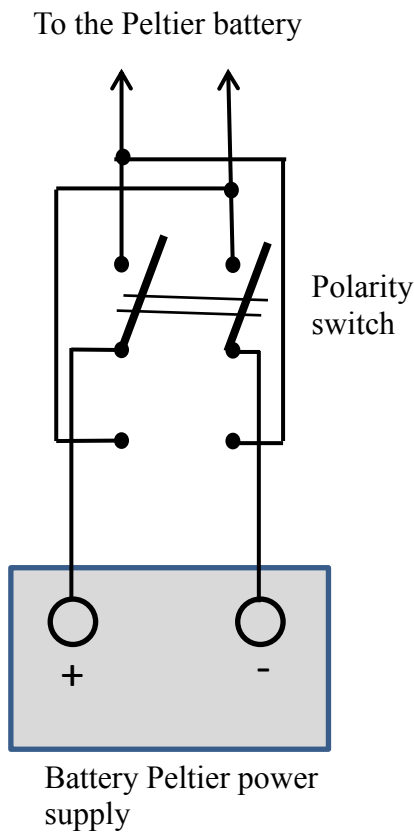


Fig.6.Power supply and switching the polarity of current through the battery

The temperature distribution was measured using a Testo 890 thermal imager. Examples of thermograms obtained in this way are shown in Fig. 7.

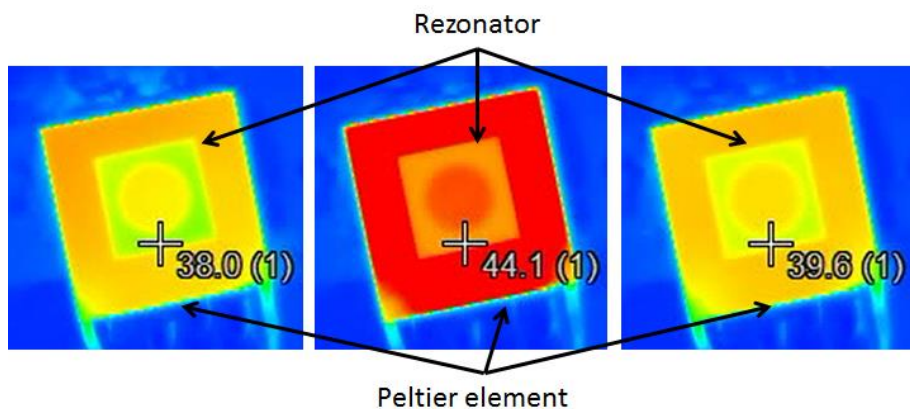


Fig. 7.. Thermal image obtained by heating and cooling of the resonator

When heated and cooled, the Peltier battery heats and cools the resonator located on its surface (Fig. 6). Heating of the resonator occurs with a delay relative to the Peltier element. At the same time, the Testo 890 thermal imager records fluctuations in the temperature field of the resonator.

This is explained by the fact that there is a dynamic equilibrium between the heat coming into the plate from the Peltier element and the heat given off by the plate surface to the environment. This dynamic equilibrium is characterized by the thermal inertia index τ , which is defined

as: $\tau = C/h \cdot A$, s, where C is the total heat capacity of the resonator; h is the heat transfer coefficient from the resonator surface to the environment; A is the surface area of the resonator.

The radiation of a heated body is described by Planck's law.

$E = c_1 \lambda^{-5} \left(\exp\left(\frac{c_2}{\lambda T}\right) - 1 \right)^{-1}$, where: E is the radiation energy, λ is the wavelength, T is the temperature, $c_1 = 2\pi^5 c_0^2 h / 15$, c_0 is the speed of light in a vacuum, h is Planck's constant, $c_2 = hc_0/k$, k is the Boltzmann constant.

Planck's radiation law applies to the so-called black body. The fundamental properties of a black body are that, firstly, it absorbs all incident radiation and, secondly, it always emits more energy than any other body at the same temperature. A model of a black body is a cavity with a hole, or some kind of depression on the surface, or a groove. When, for example, a beam of light enters the hole in the cavity, it is repeatedly reflected and absorbed by the walls of the cavity, and the probability that it will leave the cavity through the hole is extremely small (see Fig. 8).

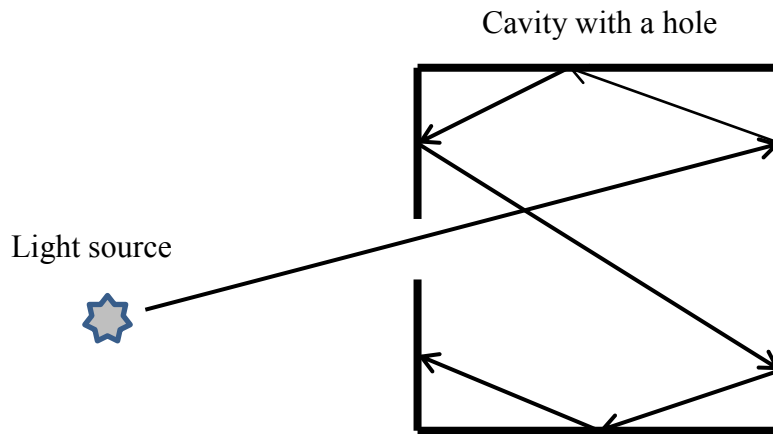


Fig. 8. Cavity with a hole as a model of a black body

In practice, the energy of this beam is almost completely absorbed by the cavity. Depressions and grooves absorb light almost as well. However, these models do not fully possess the properties of a black body, the same energy absorption as a black body, and the difference between a real body and a black body is characterized by the so-called absorption coefficient, $\varepsilon = E_r/E$, where E is the radiation energy of a black body, E_r is the radiation energy of a real body at the same temperature as a black body. Cavities are commonly used as blackbody models (Quinn, 1983).

Using the Testo 890 thermal imager, the temperature field of the resonator surface was measured during heating and cooling. Heating and cooling were controlled using a Peltier battery. The results obtained, namely the temperature change of the central part of the resonator (with relief), the temperature of its peripheral part and the temperature of the Peltier element over time are shown in the graph in Fig. 8. The difference in the obtained temperature values is due to different values of the absorption coefficients of these parts. In reality, they are at the same temperature or at least at close values. The change in temperature over time of the central part of the resonator (with relief), the temperature of its peripheral part and the temperature of the Peltier battery is shown in the graph in Fig.9. The difference in the obtained temperature values is due to the different emissivity coefficients of these objects. In reality, they are at the same temperature, or at least at close values.

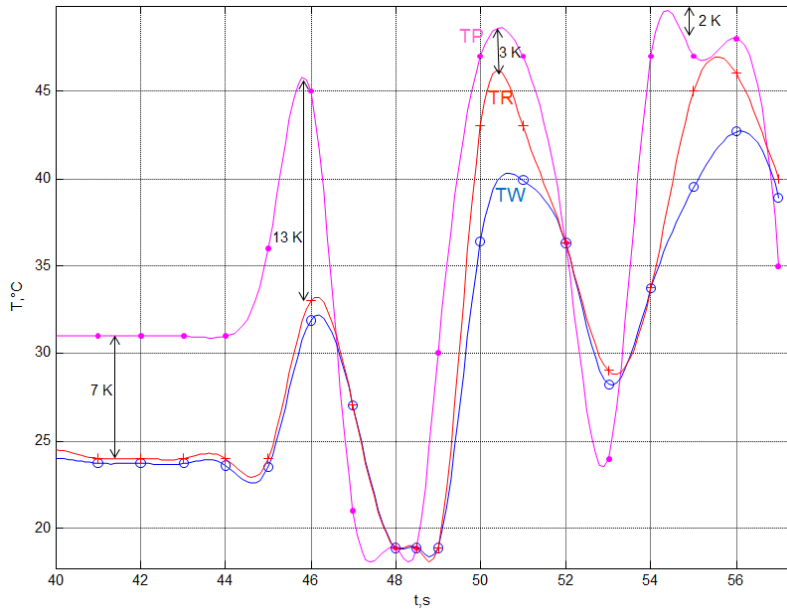


Fig.. 9. Measured temperatures:

1. Peltier batteries, magenta curve, magenta symbols “.”, TP;
2. the central part of the resonator with a relief, a red curve, red symbols “+”, TR;
3. its peripheral parts, without relief, polished silicon, blue curve, blue “o” symbols, TW

With a rapid change in the temperature of the Peltier battery, which sets the increase or decrease in the resonator temperature, the measured temperature of the central part (TR) with relief is higher than the temperature of the periphery of the plate (TW) without relief. However, their actual temperatures should be the same, since these are parts of the same object. This means that the absorption coefficient on the grooved portion of the resonator surface is significantly higher than on the smooth portion. This coefficient is not constant and depends on the heating rate due to thermal inertia. Its minimum value can reach the same value as the absorption coefficient ε of polished silicon, the maximum - the value of the absorption coefficient ε of the Peltier element surface ($\varepsilon \approx 0.8$). It should also be noted that the width of the groove on the resonator surface ($0.2 \mu\text{m}$) is incomparably small compared to the spectral sensitivity range used in the Testo 890 ($8 \mu\text{m} \dots 14 \mu\text{m}$), and such a groove with a width of $0.2 \mu\text{m}$ cannot provide absorption in the sensitivity range of the device. The radiation coefficient ε for an aluminum Peltier radiator is $\varepsilon \approx 0.8$. Based on the Stefan-Boltzmann law, the radiation coefficient for the central part of the resonator (with relief) can be determined as

$$: \varepsilon_{\text{Pelt}} \sigma T_{\text{Pelt}}^4 = \varepsilon_{\text{Center}} \sigma T_{\text{Center}}^4, \quad (1)$$

where $\sigma = 5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$ is the Stefan-Boltzmann constant

$$\varepsilon_{\text{Center}} = \frac{T_{\text{Center}}^4}{T_{\text{Pelt}}^4} \quad (2)$$

The emissivity factor of the central region of the resonator determined by formula (2) is shown in the graph of Fig. 9 at the bottom. For comparison, the temperature change graph of Fig. 8 is

repeated in the upper graph of Fig. 10.

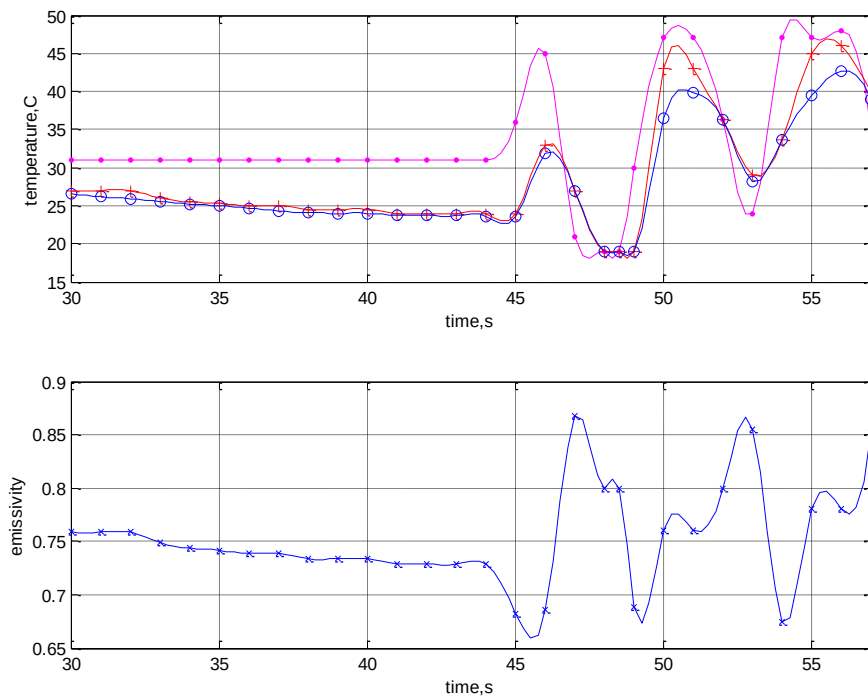


Fig. 10. Measured temperatures (upper window) and emissivity coefficient of the central area (lower window)

It is evident from the graphs that a sharp decrease in the emissivity occurs at moments of rapid change in the direction of temperature change. This can be explained by the fact that a rapid change in the concentration of charge carriers in the "grooves" region should also occur. The concentration of charge carriers in the central part of the resonator with sharp temperature changes is higher than in its peripheral regions, therefore, due to additional absorption by charge carriers, the emissivity coefficient of radiation increases here.

It is known that semiconductors have a very strong, exponential dependence of the concentration of charge carriers on temperature. Therefore, the proximity of the apparent temperature of the central part of the resonator to the temperature of the Peltier battery is explained by a sharp increase in the concentration of electrons, their concentration near the grooves and additional absorption of light by these electrons. This also explains the increase in the emissivity of the radiation of the central part with increasing temperature. True, the increase in the emissivity of the radiation occurs with some delay (about 0.5 ... 1 second), but this delay is explained by ordinary thermal inertia.

When the resonator is heated, the temperature rises, firstly, causing the concentration of charge carriers (electrons) to increase. It is known that the electron concentration in a semiconductor is highly temperature-dependent. An increase in temperature provides the energy to break covalent bonds in silicon and release electrons. As the temperature rises, the concentration of free electrons (temperature) increases. (Kittel, 1996).

Secondly, when heated, a temperature difference arises between the lower plane of the resonator, which is in contact with the heat source (the Peltier battery), and its upper plane. This, according to Fourier's law of thermal conductivity, causes a heat flow through the resonator, directed from its lower plane to its upper plane.

Assuming that the heat flow is one-dimensional and directed along the normal from the heated, lower surface to the upper one, it can be described using the Fourier law, in the form of an expression:

$$q = k(dT/dx)A, \quad (1)$$

where: q , W/m^2 is the heat flow rate through a unit surface, $k=149 \text{ W/m}\cdot\text{K}$ is the thermal conductivity of the material, silicon, T is the temperature, K , x is the coordinate along the normal to the surface, A is the surface area of the resonator, m^2 .

Expression (1) can be rewritten in a simplified version:

$$q = k(\Delta T/\Delta x)A \quad (2)$$

Then, at a resonator outer surface temperature of $t_{out} = 20^\circ\text{C}$ and an inner surface temperature of $t_{in} = 40^\circ\text{C}$, $\Delta T = t_{in} - t_{out} = 20\text{K}$.

Calculations using formula (2) yield a heat flux rate of $q \approx 1184 \text{ W/m}^2$. The heat flux through the resonator is then $Q=q\cdot A=1184\cdot 4\cdot 10^{-4}\approx 0.4736 \text{ W}$. This heat flux is then dissipated into the environment in two ways: by natural convection and by thermal radiation.

Convection law:

$$Q = h(t_{out} - t_a)A \quad (3)$$

where Q is the heat transferred per unit time, h , $W/m^2\cdot\text{K}$ is the heat transfer coefficient, and t_a is the ambient temperature. If the ambient temperature is

$t_a = 20^\circ\text{C}$, then the temperature difference $t_{out} - t_a = 20\text{K}$.

Stefan–Boltzmann radiation law: $Q = \varepsilon\sigma T^4$, W , where ε is the emissivity,

$\sigma = 5.67\cdot 10^{-8}$, $W/m^2\text{K}^4$ is the Stefan–Boltzmann constant, and T is the temperature. If the emissivity is $\varepsilon=0.8$, $T=313\text{K}$, and $A=4\cdot 10^{-4}\text{m}^2$, then the radiation power from the resonator surface has a magnitude of $Q=0.8\cdot 5.67\cdot 10^{-8}\cdot 313^4\approx 0.174 \text{ W}$;

Under the influence of the temperature difference and heat flow, electrons diffuse from the lower surface of the resonator, heated by a Peltier element, to its upper surface. This directed electron movement is nothing other than an electric current. The excited electrons emit a photon, find a vacancy, and a neutral atom is formed at the site of the resulting hole. This process continues as long as the temperature difference persists. These considerations are illustrated in Fig. 11.

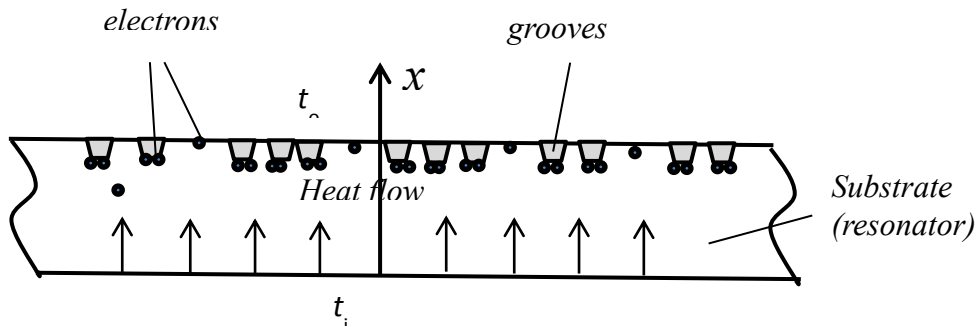


Fig.11. Movement of charges (electrons) under the influence of the temperature difference $\Delta T = t_{in} - t_{out}$ between the lower and upper surfaces of the resonator

Thus, upon heating, the electron concentration increases (Kittel, 1996), including due to the electric current generated at the resonator surface. The most favorable position for near-surface electrons is at the groove bottoms, as the distance from them to the heated, lower part of the resonator is lower than from its upper surface in adjacent areas. Therefore, the electron concentration in the groove area is significantly higher, and radiation absorption due to absorption by electrons is also higher.

It is known that the absorption of light by free electrons in semiconductors increases with increasing wavelength (Seeger, 1982).

4. Conclusion

An experimental study was conducted on a device made from a silicon wafer measuring 20 mm x 20 mm x 1 mm with a regular relief of annular grooves 0.2 μm wide and 0.8 μm deep on its surface, constructed by multiple repetition and scaling using affine transformations that form a pattern obeying the laws of self-similarity and scale invariance (Kopyltsov, Lukyanov, 2007, 2022). Previously, these studies simulated the behavior of such an object, using the assumption that when an electric field is applied to such a wafer, it behaves similarly to devices such as MOSFETs.. This similarity lies in the fact that in such a transistor, based on the phenomenon of electric polarization in an electric field, a space charge arises and a transition from an electrically neutral state to an electrically charged one occurs. A strong dependence of the concentration of electric charges in a semiconductor on temperature is also known. Devices such as semiconductor temperature sensors operate on this basis. In the object under consideration in this article, the groove configuration results in an uneven distribution of electric charges on the wafer surface with increasing temperature: charges gravitate toward the groove-based areas, as it is energetically more favorable for them to reside in the groove zone than on the surface (Fig. 3). This results in the apparent temperature in the wafer's center being higher than at its periphery. The experiment utilized periodic heating using a Peltier array. The wafer's surface response was recorded using a Testo 890 thermal imager. The surface temperature field was measured. When heated, the surface begins to emit electromagnetic radiation according to Planck's radiation law. Since the maximum wafer temperature reached during heating did not exceed 50°C, this radiation lies in the infrared range. To determine the temperature from this radiation, a device with infrared sensitivity—a thermal imager—is required. The Testo 890 thermal imager was used to measure the temperature field of the resonator surface during heating and cooling. Heating and cooling were controlled using a Peltier element. It turned out that the measured temperature values of the central part of the resonator (with the relief) significantly exceeded the temperature values of its peripheral part. However, in reality, all parts of the plate have the same temperature or, at least, similar values. This can only be explained by the fact that the absorption coefficient of the central part of the plate with the relief is significantly higher than the absorption coefficient of the peripheral part (Fig. 8). This result cannot be explained solely by the presence of radiation-absorbing grooves, since their width of 0.2 μm and depth of 0.8 μm do not allow them to absorb in the wavelength range within which the Testo 890 is sensitive (8 μm to 13 μm). The surface relief, however, allows for good absorption in a wavelength range of fractions of a micrometer. However, grooves with a width and depth on the order of fractions of a micrometer are unable to absorb radiation in the range of 8 to 13 μm , within which the Testo 890 is sensitive. This suggests that another absorption mechanism exists. This can be explained by absorption by electrons (Seeger, 1982), the concentration of which in the central part of the grooved plate is significantly higher than in the peripheral parts. The experimental results (Figure 7) clearly confirm this. These photographs, in the IR spectrum, show that the central part of the resonator, with its relief, has the same temperature as the surface of the Peltier battery. The experimental results presented in this article demonstrate the adequacy of the model of

interaction between the resonator and electromagnetic radiation, previously applied in numerical simulations (Kopyltsov, Lukyanov, 2007, 2022).

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