1. Introduction
One of the main tendencies in modern semiconductor technology is development of growth methods to produce thin layers and nanoheterostructures [1]. Molecular-beam epitaxy is the most suitable technique to fabricate such structures [2]. Despite of the high quality of the grown structures, there are some problems which make this method not suitable for mass production [3]. These lacks are small transfer coefficients of main substances and impurities, obtaining difficulties of uniform thickness layers on large substrates. Therefore, it is important to development another alternative growth methods such as ion-beam crystallization [4-6], ion-beam sputtering [7-9], laser beam crystallization [10] and zone sublimation regrowth [11]. The goal of this work is to development of zone thermal recrystallization method using a germanium discrete source for producing uniform thickness layers on large substrates.

2. Calculation
The main idea of our experimental set up is shown in figure 1. The local sources are arranged hexagonally, where \(2r\) is the diameter of the local sources, \(h\) is the minimal distance between the neighboring local sources, \(T_1\) and \(T_2\) are temperature of the evaporator and the substrate respectively, \(d\) is the thickness of the deposited layer. The filling factor \(\gamma\) is one of the important characteristics. The filling factor is the ratio of the area of all local sources to the area of the wafer where the evaporators are located. The value of \(\gamma\) indicates how many times the flow of the evaporating material is weakened.
if the discrete source is used instead of a continuous one. We used a discrete source with hexagonal
arranged local evaporators and fill factor for this case is defined as \( \gamma = \frac{2\pi^2}{\sqrt{3}(2r+h)^2} \).

![Diagram](image)

**Figure 1.** Discrete source-substrate system

Deposition probability \( \omega \) for a molecule evaporated from a circular local source to a point of
the substrate, is defined as

\[
\omega(\rho) = \frac{1}{2} \left[ 1 - \frac{l^2 - r^2 + \rho^2}{\sqrt{(l^2 - r^2 + \rho^2)^2 + 4r^2l^2}} \right],
\]

where \( \rho \) is the distance from the center of the projection of the local source on the substrate to the
point on the substrate. The layer thickness depends on the technological and geometrical parameters
and is described by the equation:

\[
d(x,\phi) = v_{m} \cdot t \left\{ \omega(\rho_0) + \sum_{n=1}^{k} \sum_{m=0}^{\frac{n}{2}} \sum_{z=0}^{\frac{5}{2}} \omega(\rho) \right\},
\]

where \( \rho_0 = x, \rho_i^2 = x^2 + l^2(n^2 - nm + m^2) - 2xl\sqrt{n^2 - nm + m^2} \cdot \cos(\arctg(\frac{\sqrt{3}m}{2n-m}) + z \frac{\pi}{3} - \phi) \).

The position of \( i \)-th local source in the hexagonal configuration is characterized by three
coordinates \( n, m \) and \( z \). Here \( n \) is the serial number of the hexagon, \( z \) - serial number of the side of a
hexagon, \( m \) is the serial number of the source located on the side of the hexagon. The value \( k \) is
determined by the diameter \( D \) of the discrete source. For the hexagonal discrete source \( k \) is equal to 3.
The central local source described by the first separate term in equation (2). The dependence of the
layer thickness on temperature-time mode determined by the factor \( v_{m} \cdot t \), where \( v_{m} \) - the rate of
evaporation from the surface of each local sources, \( t \) is the time of evaporation. In the derivation of
equation (2) it is assumed the additivity of molecular flows from the local sources. It does not take into
account that the surface diffusion and the atoms multipath from the source and substrate. These factors
can lead to a weakening of the modulation of thickness deposited layer \( d(x,\phi) \). The position of the
point, in which is calculated \( d \), is given by polar coordinates \( x \) and \( \phi \). To determine the non-uniformity
of the grown layer is sufficient to consider the direction, which is given by formula \( \phi = \pi/6 + q\pi/3 \),
where \( q \) is an integer.

3. Experiment and discussion

Experimental verification of the possibility of obtaining uniform thickness layers on large
substrates was carried out using germanium as a model material. The evaporator is made of chemical
pure finely porous graphite. The system of the local sources with hexagonal geometry was drilled in
the evaporator. Graphite vapor pressure at the operating temperature of the deposition process is not
more than \( 10^{-9} \) Pa. Graphite is essentially insoluble in germanium and quite easily handled
mechanically. After machining the graphite wafer was hardened by the pyrolytic carbon layer. Then
this hardened wafer was thermal cleaned in a vacuum. The 100 mm standard polished silicon wafers
with crystallographic orientation (100) is used as substrates. Further purification was achieved by
sublimation etching of the substrate at the temperature of 1150 °C in a vacuum. The drilled local sources were loaded with germanium powder. Then the loaded germanium powder was melted. Note that the vapor pressure of liquid germanium during the deposition of the layer in the temperature range 650 to 920 °C is less than 10^{-2} Pa. In this experimental conditions $l/R < 10^{-3}$, $l/\lambda \approx 10^{-4}$. Scanning electron microscopy were used to investigate the thickness of the grown layers using position mark technique [12].

The non-uniformity of the deposited layer is calculated by the formula:

$$\delta = 1 - \frac{d_{\text{min}}}{d_{\text{max}}}.$$  \hfill (3)

The calculated (curves) and experimental (crosses) results of $\delta$ for the different parameters of $r$ and $l$ are shown in Figure 2. The curves 1-3 is for the center of the substrate and the curves 4-6 is for the edge of the substrate.

![Figure 2](image_url)

**Figure 2.** The dependence of non-uniformity thickness on the distance between the source and the substrate $l$ at different radius of the local sources $r$.

The ordinate axis is expressed in term of the relative layer thickness $d(l)$. Increasing the parameter $l$ at $x = 0$ leads to a decrease in the layer thickness $d_1(l)$. Otherwise, increasing the value of $l$ at $x = L/2$ leads to an increase in the layer thickness $d_2(l)$. At the point $l = 2.5$ mm, the values of both functions $d_1(l)$ and $d_2(l)$ are equal. Under these conditions the non-uniformity for local sources with radius $r = 1$ mm is less than 0.03. In other words, the deposited layers becomes uniform.

Thereby a model of zone thermal recrystallization of germanium on silicon from a discrete liquid-phase source has been developed and an experimental verification of theoretical calculations has been carried out. It is established that an increase in the thickness of the growth zone $l$ most significantly affects the inhomogeneity of the grown layer. It is shown that at thicknesses less than $l < 1$ mm the inhomogeneity of the layer is more than 30% for all technologically realizable radiiuses of local evaporators and the distances between them. In the general case an increase in the distance between the local evaporators $h$ leads to a deterioration in the homogeneity of the layer, but essentially depends on the distance between the local evaporators $r$. An increase in the radius $r$ also increases the heterogeneity of the growing layers.
4. Conclusions
The method of zone thermal recrystallization from a discrete source to obtain uniform thin semiconductor layers was proposed. The method uses the system of geometrical arranged local sources filled with liquid germanium. It is shown that to achieve uniformity of better than 97% the critical thickness must be equal to $l_c = 1.2$ mm for a hexagonal arranged system of round local sources with the radius of $r = 0.75$ mm and the distance between sources of $h = 0.5$ mm.

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References
[1] Zhukov A E, Maximov M V, Savelyev A V, Shernyakov Y M, Zubov F I, Korenev V V, Martinez A, Ramdane A, Provost J-G, Livshits D A 2013 J. Appl. Phys. 113 233103
[2] Nikiforov A I, Timofeev V F, Pchelyakov O P 2015 Appl. Surf. Sci. 354 450
[3] Shengurov V G, Denisov S A, Chalkov V Y, Buzynin Y N, Drozdov M N, Buzynin A N, Yunin P A 2015 Tech. Phys. Lett. 41 36
[4] Chebotarev S N, Pashchenko A S, Williamson A, Lunin L S, Irkha V A, Gamidov V A 2015 Tech. Phys. Lett. 41 661
[5] Lunin L S, Chebotarev S N, Pashchenko A S, Dudnikov S A 2013 Journal of Surface Investigation 7 36
[6] Lunin L S, Sysoev I A, Alfimova D L, Chebotarev S N, Pashchenko A S 2011 Inorganic Materials. 47 816
[7] Lunin L S., Chebotarev S N, Pashchenko A S, Bolobanova L N 2012 Inorganic Materials 48 439
[8] Chebotarev S N, Pashchenko A S, Lunin L S, Zhivotova E N, Erimeev G A, Lunina M L 2017 Beilstein Journal of Nanotechnology 8 12
[9] Chebotarev S N, Pashchenko A S, Lunin L S, Irkha V A 2016 Nanotechnologies in Russia 11 435
[10] Balandin V Yu, Aleksandrov L N, Dvurechenskii A V, Kulyasova O A 1994 Phys. Stat. Sol. (a) 142 99
[11] Lozovskii V N, Lozovskii S V, Valov G V 2013 Tech. Phys. Lett. 39 175
[12] Lozovskii V N, Chebotarev S N, Irkha V A, Valov G V 2010 Tech. Phys. Lett. 36 737