Optimization of one- and two dimensional masks in the optical lithography

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Abstract

The goal of this work is to present the usage possibilities of the evolution algorithms in the microchip manufacturing. Nowadays, the optical lithography is the standard tool in the production of microelectronic circuits. One of the steps of the process is the illumination of a mask (exposure) where the masks pattern is transferred onto the object surface. The Fraunhofer Institute in Erlangen have developed a simulation program named Simulation of Optical Lithography in three Dimensions (SOLID) in the past few years. With the help of given parameters this system is able to model and analyze the lithography procedure. The next step of the project is the automatic optimization of these parameters. The big number of parameters characterize the complexity of the task. The theme of this paper – within this field – is the optimization of the layout of the masks. A computer program is developed, which uses genetic algorithms for this optimization. The program is working as a module of SOLID.

1 Introduction

Nowadays, lithography simulators are used in many research laboratories in the semiconductor industry and in governmental institutions to foster the development of new optical lithography techniques (for example, another composition of photo-resists).

The Fraunhofer Institute (Integrated Systems and Device Technology) has developed a simulation program (so-called Simulation of Optical Lithography in three Dimensions (SOLID)). With the help of given parameters this system is able to model and analyze the lithography procedure. The next step of the project is the automatic optimization of those parameters. The problem is the big number of parallel optimized parameters, which characterize the complexity of the task.

A mask is illuminated in a step of the optical lithography and its pattern is transferred onto the object surface. A project was started by the Fraunhofer Institute to develop software that optimizes this mask with the help of evolutionary algorithms.

This paper presents the optimization of the so-called *one- and two dimensional masks*. One dimension signifies, in this case, that the mask consists of vertical lines and that we only optimize the horizontal structure of the mask (the number, width and distance of the lines). In the two dimensional case the mask can be arbitrary.

We developed a program that optimizes the one- and two dimensional masks and works as a module of SOLID. Our program uses *genetic algorithms*.

The following section of the paper introduces the main principles of optical lithography and the theoretical basics of mask optimization. Section 3 explains shortly the functionality of evolutionary algorithms. The last two sections deal with the developed program. The parts of the program are described in Section 4. Finally, Section 5 presents the experimental results of our software.

2 Optical lithography

Optical lithography has been the standard technology of manufacturing microelectronic components for decades. The electric and optical devices have continuously bigger capacities, and they demand smaller and smaller feature sizes. Nowadays this feature size can be below 0.15 micron.

New techniques are developed in research-laboratories to reach smaller feature sizes. The innovation and testing of these improvements cost a lot of money and time. Thus, optical lithography is *simulat*ed with the help of computers in several research-laboratories.

2.1 The lithographic process

Optical lithography consists of physical (first of all optical) and chemical processes. The process flow can be partitioned into nine steps as can be seen in Figure 1 but only the process of the exposure is described in detail, as it is the step in which our computer program works. The bottom grey region illustrates the silicon wafer in Figure 1. A thin silicon oxide (dark grey) is placed on this wafer. The aim of the entire process is to shape a certain mask layout into this layer [1].

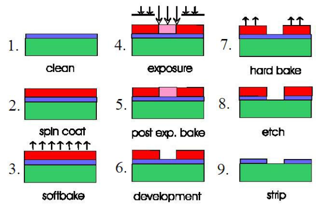

Figure 1: Basic steps of a photolithographic patterning process

The fourth step is the most critical part of the process. A mask is illuminated, thus light rays can only reach some areas of the photo resist. The inhibitor decomposes in those areas of the resist (non chemically amplified resist). In this way, the layout of the mask is transferred into the resist material.

The projection system is a complex system of lenses and mirrors. Figure 2 sketches the scheme of their structure. The system always contains a light source, a condenser system and projection optics (projection lens, aperture stop). The condenser lenses are responsible for the homogenous illumination of the mask. The projection lens reproduces the mask on the wafer [1].

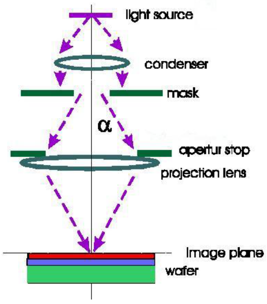

Figure 2: Principal sketch of a lithographic imaging system

2.2 Optical Enhancement Technologies

The object of the optical enhancement technologies is to modify the structure of the masks in order to assure that the resulting feature in the silicon oxide layer is equivalent to the planted one. The layout of the mask can be differed from the target layout. Recently the design of the mask layout has become important, therefore our project was carried out in good time.

The optical enhancement technologies can be classified into two sections. The optical proximity correction (OPC), deals with the layout of the mask. It optimizes the position, transmittance, and size of the elements. The transmittance value of an element signifies how much light can get through the element . The *phase shift masks* – which is the other class of optical enhancement technologies – focus on the vertical (cross-section) structure of the mask.

Optical Proximity Correction

When two mask patterns get closer to each other the light rays can be blended when they are in the same phase (the same point of their waveperiod).

This interaction of light rays explains the so-called *iso-dense bias* phenomenon:

Two masks are compared (Figure 3):

- An *isolated mask* has only got one isolated line.
- A *dense mask* has more parallel lines. The width and distance of these lines are equal to the linewidth of the line of the isolated mask.

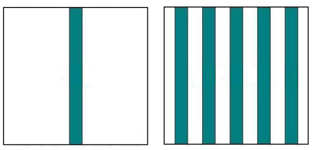

Figure 3: The layout of an isolated and a dense mask

The *aerial image* is the intensity of the blended light close to the wafer surface. These two patterns have different aerial images (Figure 4 shows this difference). The images differ in the width and steepness of the waves as well. This phenomenon is called iso-dense bias [2].

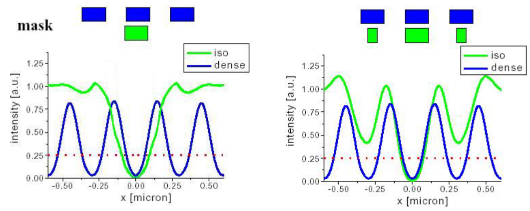

Figure 4: Aerial image of an isolated and a dense mask with assist lines. Their linewidths are equal.

The *sub resolution assists* try to reach better aerial images through so-called assist lines. These assist lines are placed close to the single line on the mask. Therefore the mask has become more similar to a dense mask, and the steepness and width of its intensity-wave aerial image are altered.

The rounded corners of a rectangle's image build another problem. Thus rectangles (so-called "hammerheads") are placed on the corners of the line on the mask to solve this problem. This procedure is known as OPC serif in literature. Figure 5 illustrates aerial images with and without hammerhead. On this figure the black line describes the mask layout, and the different grey-levels illustrate different intensity-levels [2].

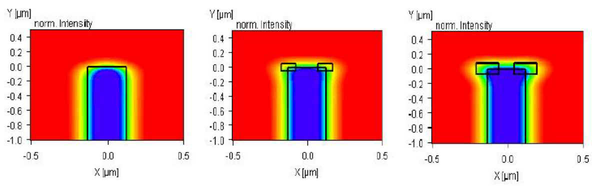

Figure 5: Aerial images of masks with different sizes of hammerheads

Phase Shift Masks

There is a diffraction phenomena as well, when two mask patterns get closer to each other because two diffraction patterns are blending into one when they are in the same phase.

To prevent this diffraction, one of the openings is covered (See Figure 6) with a transparent layer. This layer shifts one of the sets of exposing rays out of phase. In this case the mask is already not a binary mask [5].

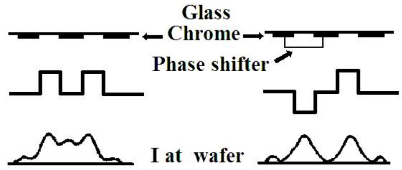

Figure 6: Light intensity patterns (a) without phase shifting and with phase shifting(b)

3 Evolutionary algorithms

In situations where an analytic solution of a problem is impossible or, for reasons of efficiency, cannot be found without unreasonable effort, evolutionary algorithms are often used in order to find the best approximation solution possible. In analogy to Darwin's natural evolution, approximation solutions are regarded as generations of individuals that are subdued to a variation-selection cycle as long as a sufficiently good solution is found [4]. Regardless of the problems to be solved, there are three important principles: Dualism genotype-phenotype: each individual has two different types of representation: the genotype is the representation of the individual during variation. The phenotype is used for fitness evaluation during the selection phase. Discrete codification: the genotype is regarded as a chain of signs in a finite alphabet. Sexual reproduction: during variation, not only some individuals are modified. New individuals are created through the right combination of various successful parental individuals. In spite of these common features, there are a number of points that have to be solved again for each problem. The success or failure of this process is very important for the efficiency of the respective system and the quality of the results obtained:Transformation between phenotype and genotype, fitness evaluation, Selection mechanism, Variation operators and Balance selection - variation.

4 The description of the developed program

For the easier understanding of the following, we have to introduce three definitions.

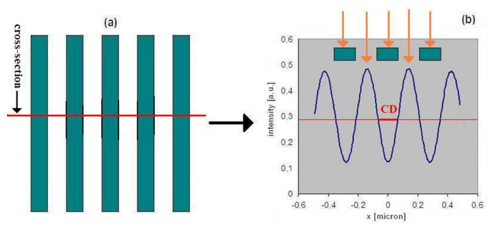

Figure 7: (a)A dense mask and (b)its intensity curve with a CD value on a certain cross-section

- The **intensity curve** is a cross section of the aerial image. The intensity of the light is greater on the aerial image where the light can get over the mask (the white areas of Figure 7(a)). Figure 7(a) depicts a dense mask and Figure 7(b) the intensity curve to the signed cross-section.

  This curve already holds the characteristics of the feature on the end of the optical lithography process. Thus we analyze only it in the following.
- **CD** values are defined as the width of the intensity-wave on a certain intensity-level of the intensity curve. It is illustrated in Figure 7(b). It is equal to the average of the circuit's linewidth when it is examined on from appropriate level.
- Focus is the distance of the light source and the imaging plane. If it is not well calibrated the image falls over the surface or in the material. If we diverge from the best focus situation the intensity waves will get flatter. The deviation of focus from the best focus situation is called **defocus** and it is a parameter of exposure.

4.1 Mask representation forms

The module has four different mask representation forms, 2 one dimension cases and 22 two dimension cases. . Each of them solves a different problem.

One dimensional continuous case

In the one dimensional case the program's input is a dense mask. The program searches for the best mask which results in one circuit line with the CD value of the dense mask.

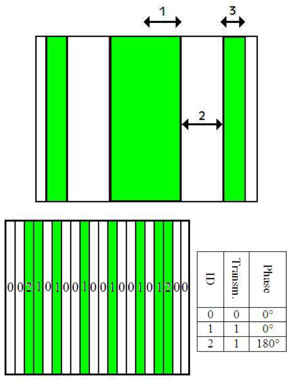

Figure 8: The output mask in the one dimensional continuous and discrete case

In the first version, the output mask is an isolated mask with two assist lines as described in section 2.2. Figure 8 illustrates the three continuous optimization parameters of the mask. The mask is symmetrical, therefore the two assists have the same distance and width.

One dimensional discrete case

In the second representation form the output mask consists of a large number of elements (we tested our program with 160). Each element has a fixed position and size as illustrated in Figure 8. The program alters their transmission and phase values. We used binary masks, thus the transmission value is 0 or 1, so light can or can not get through the element. The transmission and phase values are independent from each other, so they can be given in pairs to an element. The list of the transmission and phase pairs are given in the parameter file. In the optimization process, a discrete value is associated with each element which signifies the index in the list of pairs. The masks of this representation form are symmetrical as well. The width of the lines and the width of the mask can be set before the run of the program. These determine the number of elements.

Two dimensional continuous case

In the two dimensional cases the input mask has one square element. The program looks for the best mask which results in one square circuit element, whose horizontal, vertical and diagonal cross-sections have the CD values of the input mask. These three cross-sections of the aerial image can be seen in Figure 9. In the two dimensional continu-

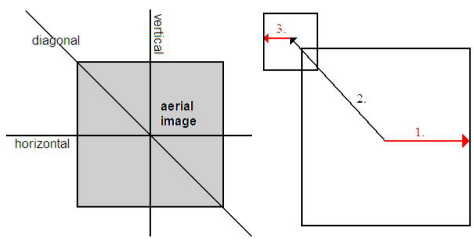

Figure 9: The cross-sections of the two dimensional cases and the output mask

ous case the output mask consists of a – center – square element and four hammerheads as described in section 2.2. The program optimizes three values. Figure 9 illustrates these three parameters.

Two dimensional discrete case
The output mask consists of a large number (we used 1600 elements in our tests) of fix placed square elements in our last representation form. Figure 10 illustrates the layout of the elements.

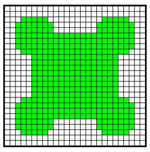

Figure 10: The output mask in the two dimensional discrete case

The program alters the transmission and phase values of the elements as presented by the one dimensional discrete case. The masks of this representation form are symmetrical round the center point.

4.2 The specification of the problem

The specification of the problem can be gives with the help of the following definitions:

1. An intensity level (so called **intensity threshold** must be determined on the input masks intensity curve where the CD is equal to the width of the input masks element. Then the program calculates the **aim CD**s from the input mask. The one dimensional cases have only one aim CD (width of the dense masks element). The two dimensional cases have three aim CDs (horizontal,vertical and diagonal). This procedure is presented in section 4.3.
2. The task of the genetic algorithm is to find the best output mask in accordance with the determined intensity threshold and aim CD(s). The fitness function (presented in section 4.5) is responsible for deciding which mask is better.

4.3 The determination of the intensity threshold

First, the program has to find the intensity level where the CD value on the intensity curve of the input mask is equal to the width of this mask's element. The points of the intensity curves are given by discrete points. Therefore the discrete point of the curve is searched that lies closest to the intensity threshold in the first step of the algorithm. For each point on the curve, the intensity of a certain point is compared with the intensity of the point in the CD_{aim} distance. We are looking for the point which has the minimum intensity-difference. The comparison is only implemented when two criteria are fulfilled:

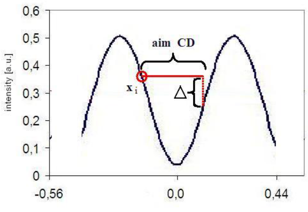

Figure 11: Searching for the nearest discrete point to the intensity level

- The first point has to be on the descending part of the curve and the second on the increasing part of it.
- Between the two points there is no point with greater intensity than the two points.

Figure 11 illustrates how the above mentioned two criteria are fulfilled. The algorithm looks for the discrete point where $\Delta_{x_i} = |I(x_i) - I(x_i + CD_{aim})|$ is minimal. $I(x)$ is the normalized intensity value at point x.

The algorithm now has to find the precise intensity level around x_d. There are two different situations. Figure 12 sketches one of them, where the second intensity is not greater than the first ($I(x_d + CD_{aim}) < I(x_d)$).

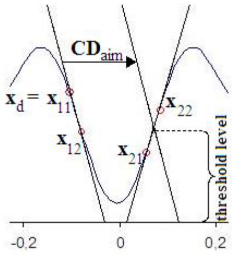

Figure 12: Searching for the precise point for the intensity level

In this figure, the points $x_{11} = x_d$ and $x_{22} \sim x_d + CD_{aim}$ are found by the algorithm. x_{12} is the next discrete point after x_{11} and x_{21} is the previous discrete point before x_{22}. We use the equation of line $y = mx + b$. The intersection point of the – with the CD_{aim} – shifted line and the other line is searched. This point of intersection's intensity is the searched intensity threshold.

From these four points the two steepnesses (m) and the values b can be calculated:

$$i = \{1, 2\} \quad m_i = \frac{I(x_{i2}) - I(x_{i1})}{x_{i2} - x_{i1}}$$

$$b_i = I(x_{i1}) - x_{i1} m_i$$

With these values the searched intensity threshold:

$$I_{thres} = \frac{b_2 m_1 - b_1 m_2}{m_1 - m_2}$$

4.4 The evolution process

The genetic algorithm module of SOLID was developed by Tim Fühner [3]. This parameterizable module is used in our program. The genetic operators are implemented in that module.

Representation of the genes
We used the four different mask representation form introduced in section 4.1. The genotype of the individuals are bit-strings in all of mask representation forms.

The optimization parameters (genes) can be given continuous values in two cases. The searching interval and the required digital precision can be given in the parameter file in these cases. These values determine the number of bits which are allocated for the gene [3].

The genes can be equal to an element of a discrete set in the other two mask representation forms. We had three different solutions to approaching the transformation of a finite value – which is not a power of 2 (sign it with n) – to bits. The simplest one was proven to the best: we use $[\log(n)]$ bits and the $2^{[\log(n)]}$ possible values are proportioned to n.

Seeding

The initial generation has several specified individuals among the randomly initialized ones. These individuals are called seeds. Our program defines one-one seed in the discrete cases (Figure 13):

- A mask with an isolated line and its linewidth is equal to the aim CD in the one dimensional case,
- a mask with one contiguous region whose sidewidths are equal to the aim CDs.

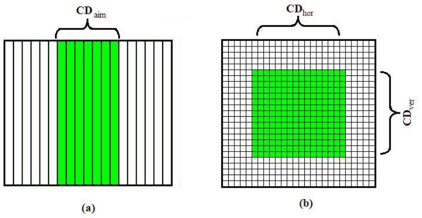

Figure 13: Seed in one (a) and two (b) dimensional discrete case

The termination criterion

The termination criterion of the genetic algorithm was the maximum number (age) of generations in our tests. The different representation forms needed different maximum ages.

4.5 The fitness function

The fitness function is responsible for the evaluation of the individuals. We defined five criteria to measure the suitability of the masks.

In the next subsections these criteria are described in detail. The first three criteria concern one intensity curve. We examine more intensity curves for one mask in two dimensional cases and in different defocus situations.

The CD criterion

The CD value on the computed intensity threshold must be equal (or as close as possible) to the determined aim CD.

The algorithm has to determine the *relevant interval* which we use for the calculation of the CD. There are three different situations which are followed from the position of the intensity threshold and the shape of the intensity curve. These situations are presented in Figure 14:

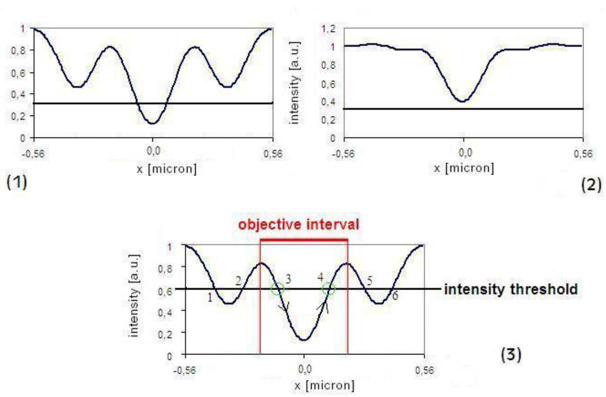

Figure 14: The different situations of the CD intervals

1. If there are exactly two points on which the intensity threshold intersects the intensity curve then these two points define the relevant interval.
2. If there is no intersection point, the entire curve lies over the threshold. The width of the "interval" is defined as zero. A special control routine is needed in the angle criterion as well.
3. If there are more than two intersection points, it is possible to choose different intervals. The experiments indicated that the following selection process works effectively: The algorithm takes a point on the monotonously decreasing part of the curve as starting point – of the relevant interval – which lies closest to the objective interval's beginning point. *Objective interval* lies on the center of the intensity curve and its width is the CD_{aim}. Point 3 of Figure 14 is chosen from points 1,3 and 5. Analogously, the ending point is the point on the monotonously increasing part of the curve, which lies closest to the objective interval's end (point 4 in Figure 14).

After the interval's starting and ending points are recognized, its width is computed. The difference between this width and the aim CD is the basis of the fitness value of this criterion.

This value has one unit (μm), but it has to be comparable with the other two criteria. Thus a factor with unit $1/\mu m$ is used ($fact_{\mu m}$). This factor is variable in the parameter files as well.

Therefore

$$f_c = |CD_{aim} - CD_{relevant}| \cdot fact_{\mu m}$$

The band criterion

In the second criterion, a band is "created" around the intensity threshold. The extremes of the curve have to lie below this band in the objective interval, and above outside this interval. The width of the band is given – as a parameter – in the percent of the intensity threshold.

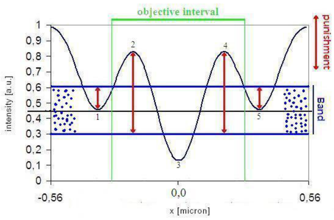

Figure 15: The punishment of extremes with the help of a band

Figure 15 contains five local extremes. Local extremes 1 and 5 are out of the objective interval but they lie under the higher bound of the band, so they are punished. Points 2 and 4 are in the objective interval and lie higher than the lower bound of the band, so they are punished as well. The extreme 3 on the middle lies within the objective interval and under the band and therefore it does not get punishment.

The extremes inside the objective interval over the lower edge of the band and the extremes outside this interval under the higher edge of the band are punished. The punishment is the difference between the intensity of the extreme and the band edge.

The usage of a factor ($fact_{int}$) is necessary again, because the punishments have a unity (a.u.). Therefore

$$f_b = fact_{int} \cdot \sum \begin{cases} I_e - I_t \cdot (1-p) & \text{if extreme is inside the objective interval and } I_e > I_t \cdot (1-p) \\ I_t \cdot (1+p) - I_e & \text{if extreme is outside the objective interval and } I_e < I_t \cdot (1+p) \end{cases}$$

where p is the bandwidth in percent, I_e and I_t signify the intensity of the extreme and the threshold.

If the entire curve runs over the intensity threshold (in the 2. case of subsection 4.5) it is always punished.

The angle criterion

The steeper is the intensity curve on the edges of the relevant interval (section 4.5) the better the mask.

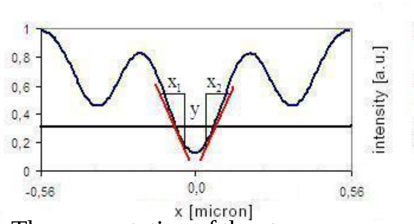

Figure 16: The computation of the steepnesses on the edges of the interval

Therefore the algorithm evaluates the steepnesses of the curve on the interval's starting- and ending points as illustrated in Figure 16. The fitness value of this criterion is the arithmetic average of these two angles.

If no starting- and ending points exist (in the 2.case of subsection 4.5) f_a is the worst possible. In this case it is zero.

Therefore

$$f_a = \frac{\arctan(y_1/x_1) + \arctan(y_2/x_2)}{2} \cdot \frac{2}{\pi}$$

The value of f_a varies between 0 and 1 and it provides the comparability of the fitness values of the criteria.

Different defocus situations

Our fitness functions have to examine the behavior of the masks in more defocus situations. The program calculates each intensity curve in each defocus situation. In the final fitness value the program calculates the arithmetic average of the fitness values from the different defocus situations.

The number of mask's elements

Our last criterion is defined in connection with the manufacturing of the mask. We consider a mask better if it consists of less contiguous regions. A contiguous region comperises elements side by side with the same transmission and phase value. f_p signifies how many contiguous regions has the mask.

The final fitness function

The weighted average of "fitness" values of these criteria is calculated. The values of the weights can be set in one of the parameter files. The calibration of these weights is one of the most interesting problems of the experiments. It is described in section 5.1.

The first two criteria are minimum problems. The second one (band) often gets zero value (see subsection 4.5). The third one (f_a) is a maximum problem and result values can be found in the [0,1] interval as described in subsection 4.5.

The CD, band and angle criteria concern one intensity curve, thus the program calculates with the arithmetical average of fitness values of the intensity curves in different focus situations and – in the two dimensional cases – with different aim CDs.

These facts were considered in the definition of the final fitness function (f):

$$f = \frac{\sum_{CD} \sum_{focus} \frac{f_c w_c + f_b w_b + (1-f_a) w_a}{n_{CD} \cdot n_{focus}} + f_p w_p}{w_c + w_b + w_a + w_p}$$

f_c is the fitness value of the CD criterion,
f_b is the fitness value of the band criterion,
f_a is the fitness value of the angle criterion (it is a maximum problem),
f_p is the number of mask's parts,

$$n_{CD} = \begin{cases} 1 & \text{in one dimension} \\ 3 & \text{in two dimension} \end{cases}$$

n_{focus} is the number of focus situations
and w_c, w_b, w_a, w_p are their weights. The optimization module of SOLID is based on maximum (the individual with greater is better) fitness values. Thus we transfer f.

$$f = 1/\max\{f,\ 10^{-7}\}$$

The usage of the max function is necessary to avoid the division by zero.

5 Experiments

The settings of parameters and the results are introduced in this section.

5.1 The fitness function's parameters

We calibrated the first part of parameters in the one dimensional continuous case. The input mask had $0.14\mu m$ linewidth and line distance. First we fixed the unit factors: two of the three intensity curves criteria exhibit a unit. The following factors were chosen to solve this problem:

$$fact_{\mu m} = 10 \text{ and } fact_{int} = 0.1$$

The setting of the fitness function's weights proved to be the most difficult exercise. The program was started 200 times. Each parameter-setting requires 5 runs, because of the random-based genetic operators. The

1.5 : 0.7 : 1.0 (CDdifference : Band : Angles)

weights proportion was proven to be the best one.

The program runs with band ±30%. We proved what happens when this value is increased to ±60%. The genetic algorithm found the same mask again as the best solution but it got band punishment in this case (by ±30% band the punishment was zero). Two defocus situations were used in our all experiments:

$$0.0 \quad and \quad 0.3$$

After the implementation of the one dimensional discrete case the new parameters were calibrated.

In the discrete cases the mask consists of a large number of elements and it is symmetrical. We should decide that we use odd or even numbers of elements. These possibilities are different in the status of the center element. When sufficient small elements are used the difference is negligible. We used $0.005\mu m$ sidewidth for the elements of the mask and the odd number of elements, but we kept – through the parameter file – these characteristics of the masks alterable.

5.2 Genetic algorithms' parameters

The evolutionary algorithm module in SOLID uses genetic algorithms and it solves maximum problems. First we had to fix the search space (the possible interval of the values) of the optimization parameters. Our input dense mask had $0.14\mu m$ linewidth and $0.14\mu m$ line distance in one dimensional cases. Therefore, we chose the search spaces of the three optimizing parameters as follows:

- for the half of the center line's width [0.02μm, 0.15μm],
- for the distance width of the assist lines [0.005μm, 0.28μm],
- and for the half of the assist line's width [0.01μm, 0.2μm].

Our input mask had 0.2μm sidewidth in the two dimensional cases. We chose the search spaces of the three optimizing parameters:

- for the half of the center squares width [0.03μm, 0.2μm],
- for the distance width of the hammerheads [0.02μm, 0.3μm],
- and for the half of the hammerheads's width [0.01μm, 0.15μm].

In the one dimensional discrete case we used elements with 0.005μm width and a masks width was 0.8μm. Thus a mask consisted of 161 elements and the algorithm had 81 optimization parameters.

In the two dimensional discrete case the mask consisted of 1681 pieces of squares with 0.02μm sidewidth (the mask was 0.4μm x 0.4μm). Thus it worked with 441 optimization parameters.

We used only two possible values for the elements of the mask in both discrete cases:

- transmission = 0.0 and phase = 0.0
- transmission = 1.0 and phase = 0.0

The most important genetic algorithm parameters are the probabilities of mutation (p_{mut}) and crossover (p_{cross}). We used one-point crossover.

The runs of the genetic algorithm were analyzed by three values in Table 1. These parameters are (from left to right):

1. The reached fitness value in the last generation. Their exact values are not important, because the algorithm can be run with different weights. Only the relation to each other is significant.
2. The generation in which the final best solution is reached.
3. The generation in which a *limit* of fitness value was stepped over. This limit was determined specially so that the CD differences (it has the biggest weight) can be regarded zero.

Table 1 illustrates several experiments of different (p_{mut}, p_{cross}) pairs in the one dimensional continuous case. The runs with each settings of the pair were repeated seven times, the table consists the averages of the seven experiments.

The best results are generated in the intervals [(0,03;0,03);(0,05;0,08)]. Note that each element of the line $p_{mut} = 0,1$ is very good, but the alteration of individuals from generation to generation are too big, thus the relation between the parents and the offsprings is loose.

Table 1 illustrates that 150 for the maximum number of generations is enough (with 31 population-size) in the continuous cases. But in the discrete cases it required greater maximal age because of the greater number of optimization parameters. It run – with 31 population-size again – during 250 generations in one dimension and 400 generations in two dimension.

In the discrete cases we got the same results by the examination of these two probabilities. Considering these facts we used 0.05 mutation and 0.05 crossover probabilities in all of our experiments.

Two selection methods are available in the genetic algorithm module of SOLID. They were compared on different mutation and crossover probability pairs. The roulette wheel selection proved to be better in all cases.

5.3 One dimension

First, the input mask had 0.14μm linewidth and 0.14μm line distance. Figure 17 presents the intensity curve of the this mask and the computed intensity threshold. The level of the intensity threshold was on 0.311461 a.u.

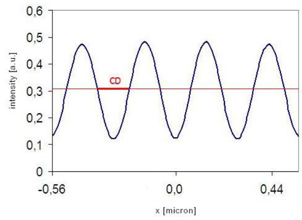

Figure 17: Intensity curve of the $0.14\mu m$-$0.14\mu m$ input dense mask and the computed intensity threshold

Two different isolated masks –with assist lines– were among the final best solutions. Figure 18 presents their intensity curves in the best defocus situation.

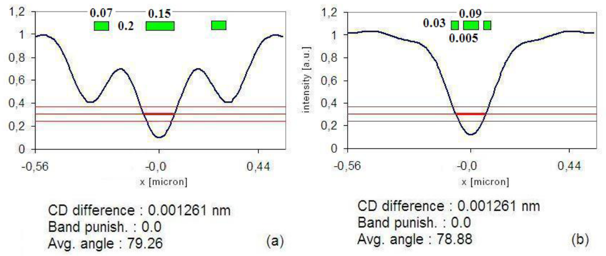

Figure 18: Intensity curves of the best output masks in the best defocus situation

But when they are analyzed with greater defocus value, only the first (case (a)) keeps its good properties.

For the purpose of checking the goodness of these masks, the program was running only with one criterion. For example the greatest reachable angle was tested with weights of 0:0:1 (CDdifference:Band:Angles), i.e. without CD and band criteria. The archived values of the best output mask (Figure 18 (a)) are very close to these reachable values:

- The CD difference 0,001261μm was proven to be the less reachable value with weights 1:0:0 (CDdifference:Band:Angles). Certainly it is only true for this special window and a number of discrete points of the intensity curve.
- The band punishment can not be less than zero.
- The greatest stiffness of the intensity curve –without CD and band criteria– was 81,12° on the edges of the interval.

The mask of the previous figures was compared with the solutions of the discrete cases genetic algorithm.

The best solution of the continuous case was proven to be the best solution in the discrete case as well. Figure 19 presents four masks. Mask 1 is the same as the solution of

p_{mut} ↓	p_{cross} →								
	0,01			0,03			0,05		
0,01	13,677	127	151	13,601	135	129	14,915	129	151
0,03	16,769	119	57	**17,496**	**135**	**44**	**17,484**	**127**	**39**
0,05	16,775	136	33	**17,424**	**142**	**54**	**17,519**	**139**	**39**
0,08	17,449	128	32	**17,517**	**125**	**151**	**17,503**	**139**	**39**
0,1	17,502	137	25	17,383	143	46	17,533	127	49
	0,08			0,1			0,2		
0,01	13,257	141	151	14,916	122	114	14,895	131	102
0,03	16,244	134	151	14,925	131	151	15,426	135	95
0,05	16,773	131	73	17,477	125	50	16,902	128	68
0,08	16,763	131	151	16,762	130	55	16,742	133	36
0,1	17,460	115	25	17,533	126	21	16,944	126	51

Table 1: Mutation and crossover probabilities

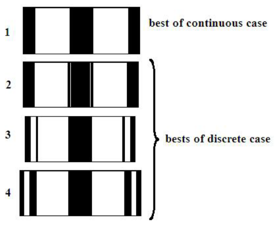

Figure 19: Solutions of one dimensional continuous and discrete cases

the continuous case. Mask 2,3 and 4 were results of evolutions, but each of them have worse steepness of intensity curve. In the CD and the band criteria they got the best possible fitness as well.

5.4 Two dimension

The program ran with the weights of the section 5.1 and the searching interval and genetic algorithm parameters of section 5.2.

Figure 20 presents the layout of the best mask which was found by the genetic algorithm.

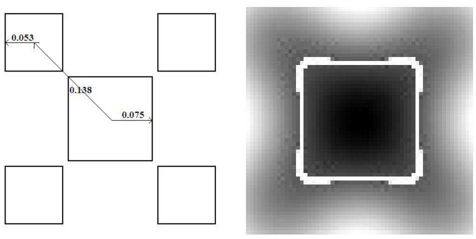

Figure 20: The best solution of the two dimensional continuous case and the aerial image (with the intensity threshold) of it

This solution has better values than the solution we expected (Figure 5 depicts this expected solution). The hammerheads of the solution of the genetic algorithm are further from the center element than we expected.

Figure 20 illustrates the aerial image of this mask in the best focus situation. The picture is dark on the low intensity and bright on the high intensity regions. The white shape signs the points where the intensities of the aerial images are equal to the intensity threshold.

We tried to reach better output masks with the discrete case than this previous solution. We let the program run with the number of elements and possible values described in section 5.2.

We cannot reach better results – similar to the one dimensional case – in the discrete case.

6 Conclusions and outlook

The Fraunhofer Institute Integrated Systems and Device Technology in Erlangen (Germany) has started a project that aims to examine the usability of evolutionary algorithms in the mask design of microchip manufacturing. The main results of this project, which optimizes one- and two dimensional mask features in the optical lithography process, were introduced in this paper.

After the main principles of optical lithography and evolutionary algorithms were described, we presented the computer program which was developed in cooperation with the Fraunhofer Institute. Finally we introduced the results of the project. We plan to follow this project in the future with:

1. the use of the developed module to optimize phase shift masks
2. the program will be expanded for test of another two dimensional shapes,
3. the optimization of the lighting source's surface.

After these steps our software – in accordance with our expectations – will be able to be utilized in the microchip industry. Several companies of the integrated circuit industry (such as Infinion MicroSystems) are interested in our work.

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