

## DISPERSION OF SU-8 PHOTOLITHOGRAPHY PROCESS FOR FABRICATION OF MICROFLUIDIC DEVICES

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*În această lucrare este prezentată o analiză a dispersiei dimensiunilor din plan pentru structuri microfluidice fabricate prin fotolitografie în fotorezistul SU-8. Este realizat un studiu experimental al influenței parametrilor de proces asupra variației dimensiunilor din plan și sunt determinate valori optime ale parametrilor de proces pentru a minimiza aceste variații. Folosind valorile determinate pentru parametrii de proces un eşantion de placete cu structuri test microfluidice este realizat. Datele rezultate din măsurările structurilor din eşantionul realizat sunt analizate statistic și este construit un model matematic al variației dimensiunilor geometrice din plan cauzate de dispersia de fabricație.*

*This paper presents an analysis of the dispersion of in plane dimensions of microfluidic structures fabricated by photolithography in SU-8 resist. An experimental study of the process parameters influence on the variation of the in plane dimensions is performed and an optimum value for process parameters to minimize this variation is determined. Using the established process parameters, a sample of wafers with microfluidic test structures is realized. Measurement results of this sample are used to perform a statistic analysis and a mathematical model of the variation of in plane geometric dimensions as consequence of the fabrication dispersion is built.*

**Keywords:** microfabrication dispersion, SU-8 photolithography

### 1. Introduction

The popularity of microfluidic research topics grew with the emergence of lab-on-a-chip systems, which revolutionized the research in chemistry and bio-medicine, by enabling the possibility of numerous experiments performed rapidly and in parallel, while consuming little amounts of reagent. The first microfluidic devices were fabricated with silicon micromachining technology. A number of microfluidic devices with integrated sensors and actuators were made in silicon [1]. With the development of lab-on-a-chip devices, the research attention turned towards manufacturing techniques using low cost polymeric materials [2]. Polymers are mouldable to complex shapes and dimensions and have good isolation properties. They can be made inert to interaction with biomolecules and can be modified to have a uniform surface property for electroosmotic flow

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(EOF). Hence, polymers are better suited for many microfluidic applications because of their low cost, chemical inertness, low electrical and thermal conductivity, suitability for surface modification, and compatibility with biological materials [1,2].

Most of today's microfluidic devices are application specific, which requires that unique devices must be developed for each application with their own specific requirements. In the present, it does not exist a standardized technology for microfluidic devices [3, 4]. Standardization of fabrication technologies implies definitions of standards on manufacturing tolerances, especially for the new polymer micromanufacturing techniques, that have not yet been fully established, while most of the data is 'in-house' determined [5]. A large number of microfluidic devices have been designed for applications like medical diagnosis or safety biochemical applications. For this type of applications, fault tolerance is critical to ensure low false positive and false-negative detection rates. Recently, fault tolerance analyses and design for manufacturability methodologies for microfluidic systems have been proposed, although very limited work on the subject has been reported to date [7]. The fabrication dispersion leads to the appearance of deviation of the geometrical parameters of the fabricated device from the designed values, which at its turn leads to variations of the performance parameters. These variations in performance need to be known and controlled. For this reason, in this paper it is proposed a mathematical model for quantifying the fabrication dispersion for one of the most common fabrication processes for manufacturing microfluidic devices: SU-8 photolithography.

Photolithography is the most used process for the fabrication of microfluidic devices. It can be used either as main fabrication process for realizing microfluidic components in a photoresist polymer [1, 2, 8], or as an intermediary fabrication step for realizing master structures for a replication process or for obtaining etch masks for volume microfabrication [1, 2]. One of the most common materials for fabricating microfluidic devices is SU-8, an epoxy based negative photoresist, with a high quality substrate adhesion, which allows the realization of structures with high aspect ratios (up to 10:1)[9, 10]. SU-8 is widely used either as main material for fabricating microfluidic structures or for fabricating master structures for replication processes.

All the experimental tests presented in this paper and the measurements of the fabricated structures have been performed in the MINAFAB technological facility of IMT-Bucharest.

## 2. Study of the process parameters influence on the variation of in plane geometrical dimensions of microfluidic test structures

To study the dispersion of the SU-8 photolithography process a test mask has been designed with the most common geometrical configurations used for microfluidic devices (fig.1) [11]. These geometrical configurations are various microchannel shapes: straight, meander and saw-teeth microchannel geometries, passive microvalve series with rounded and straight walls, microfilter and various ramified microchannels: 'T'-shaped, straight 'Y'-shaped and rounded 'Y'-shaped. The characteristic dimensions of typical microfluidic devices are of order 10 $\mu\text{m}$  – 100 $\mu\text{m}$  [12]. Therefore, the designed geometrical configurations have been repeated on the test mask with various dimensions: 10 $\mu\text{m}$ , 20 $\mu\text{m}$ , 50 $\mu\text{m}$ , 100 $\mu\text{m}$ , 150 $\mu\text{m}$  and 200 $\mu\text{m}$ .

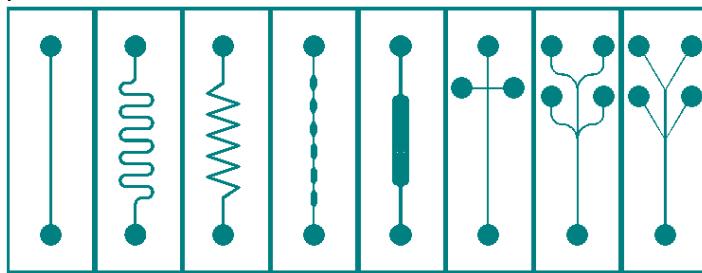


Fig. 1. Designed geometrical configurations for the test mask

The material used for the fabrication of microfluidic test structures is SU-8 2050. Using this type of SU-8, it is possible to obtain structures with depths between 10 $\mu\text{m}$  and 200 $\mu\text{m}$ . The baseline SU-8 photolithography process has the following steps [1, 10, 12]:

- ◆ Substrate pretreatment - To obtain maximum process reliability, substrates should be clean and dry before applying the SU-8 resist
- ◆ Resist spin coating – the spin speed is the process parameter that influences the thickness of the SU-8 layer
- ◆ Soft bake – after coating the SU-8 layer must be treated on a hot plate to evaporate the solvents and prevent bubble formation; the treatment is done at two temperature steps: 65°C, respectively 95°C and the treatment time depends on the thickness of the resist layer
- ◆ Exposure – SU-8 cross-linking is obtained at near UV (350-400nm) radiations
- ◆ Post exposure bake - must be performed to selectively cross-link the exposed portions of the film
- ◆ Develop – developing is performed by immersion in SU-8 developer to remove the unexposed areas

- Hard bake – to obtain improved adhesion of the SU-8 layer on the substrate

The variation of the in plane dimensions of the microfluidic structures fabricated by SU-8 photolithography is influenced by the exposure step and the process parameter that needs to be optimized in order to have minimum variation is the exposure dose. The developing time does not significantly influence the geometry of the microfluidic structures. Because SU-8 is a negative photoresist highly sensitive to UV radiation, by exposure strong cross-linking is formed and over developing appears for much higher times then recommended. Under developing can be easily corrected by re-immersing the probe in SU-8 developer for a supplementary time.

The dispersion of the in plane geometrical dimensions of a microfluidic structure depends on the exposure dose [10, 13], which is proportional with the intensity of the lamp, measured in  $\text{mW/cm}^2$  and the exposure time, measured in seconds. For the experimental trials it has been used a lamp with a measured intensity of  $23\text{mW/cm}^2$  and an average i-line intensity of  $7.9\text{mW/cm}^2$ . A first set of experiments has been performed using exposure times of: 10s, 15s, 20s and 25s. It has been observed that the best results have been obtained for the lowest times: 10s and 15s. For exposure times above 20s the in plane dimensions of the microfluidic test structures resulted to be smaller with over  $5\mu\text{m}$  then the dimensions of the mask and the structures with the lowest dimensions ( $10\mu\text{m}$  and  $20\mu\text{m}$ ) did not develop (fig. 2 a); b)). Also, an exfoliation of the SU-8 layer has been observed in these cases. All these observations lead to the conclusion that the exposure dose was to high.

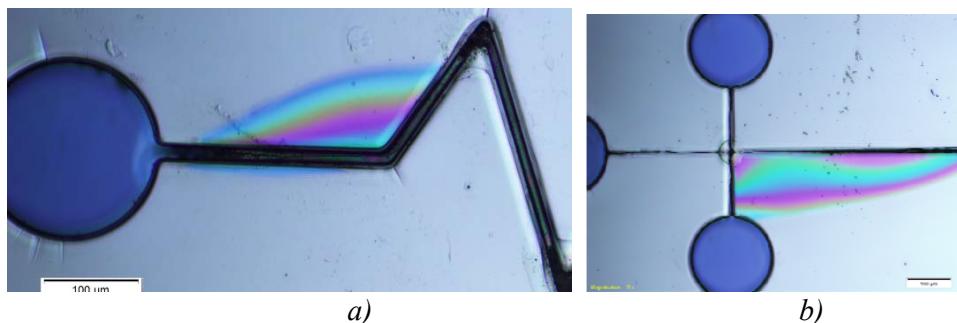


Fig.2. Microchannel with the designed width of a)  $20\mu\text{m}$ ; b)  $10\mu\text{m}$  exposed for 20s

For the exposure time of 10s the in plane geometrical dimensions of the microfluidic test structures resulted to be smaller then the corresponding mask dimension with approximate  $2\mu\text{m}$  (fig. 3 a)) and the test structures with designed widths of  $10\mu\text{m}$  did not develop (fig. 3 b)). Also these observations indicate that a 10s exposure time is higher then optimum.

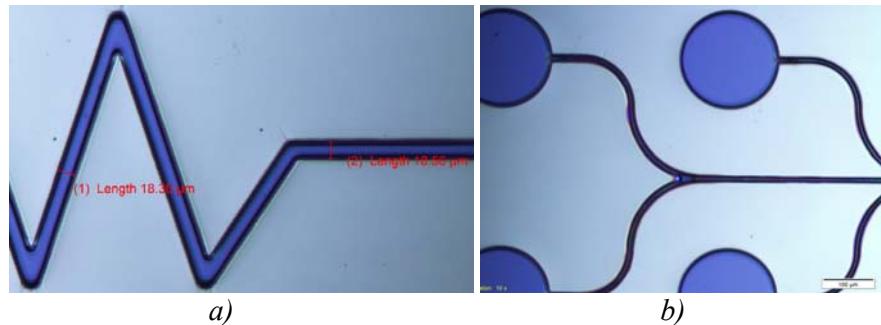


Fig. 3. Microchannel with the designed width of a) 20  $\mu\text{m}$ ; b) 10  $\mu\text{m}$  exposed for 10s

For an exposure time of 10s it has been observed that the vertical profile of the SU-8 test structures is not rectangular, but it has a trapezoidal shape (fig. 4). This is also an indication of over exposure.

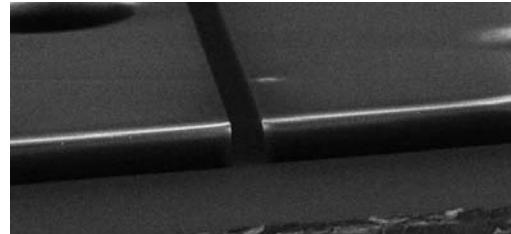


Fig. 4. For an exposure time of 10s it has been obtained a trapezoidal vertical profile of the SU-8 microfluidic test structures

A new set of experiments has been performed using an exposure time of 8s. In this case have been observed symmetric variations of about  $\pm 1 \mu\text{m}$  of the in plane dimensions of the test structures and all the structures from the test mask have developed (fig. 5).

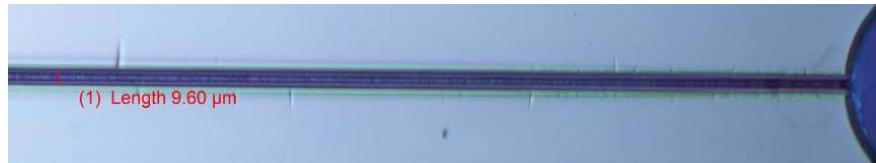


Fig. 5. Microchannel with the designed width of 10  $\mu\text{m}$  exposed for 8s

The vertical profile of the test structures obtained with an exposure time of 8s has a rectangular shape (fig. 6) as it should be in optimum conditions, fact that confirms that the exposure dose has an optimum value.

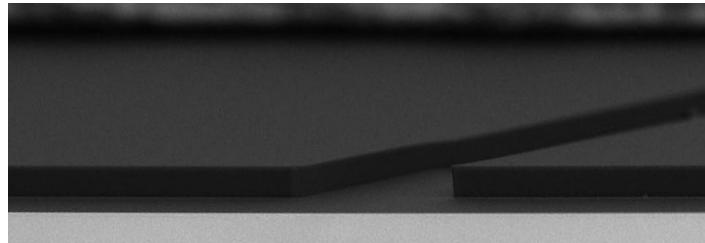


Fig. 6. For an exposure time of 8s it has been obtained a rectangular vertical profile of the SU-8 microfluidic test structures

Based on the experimental observations it has been determined that the optimum exposure dose for the given work conditions is obtained at an exposure time of 8s. The other process parameters that have been used for fabricating microfluidic structures by photolithography in SU-8 on a  $\text{SiO}_2$  substrate are presented in the list below:

- ◆ Resist spinning is done at the spin speed regime of 500rpm for 5s, followed by 3000rpm for 60s
- ◆ Soft bake - at  $65^\circ\text{C}$  for 5 min, and at  $95^\circ\text{C}$  for 10 min
- ◆ Exposure – UV exposure using a 350W lamp with an intensity of  $\sim 23\text{mW/cm}^2$  for 8s
- ◆ Post exposure bake at  $65^\circ\text{C}$  for 2min and at  $95^\circ\text{C}$  for 8min
- ◆ Develop – SU-8 developer immersion for 3.5 -4 min
- ◆ Hard-bake at  $150^\circ\text{C}$  for 20min

### **3. Statistical analysis of the dispersion of SU-8 photolithography process**

Using the process steps and the optimum determined process parameters described in the previous section, a statistic sample has been build by processing 7 wafers with microfluidic test structures. On each sample approximately 20 measurements of in plane dimensions of the microfluidic test structures have been performed using the scanning electron microscope (SEM TESCAN VEGA II LMU).

Since on the test mask there are structures with designed dimensions varying from  $10\mu\text{m}$  to  $200\mu\text{m}$ , the measured values have to be grouped in 6 data sets accordingly to the designed dimension of the structure:  $10\mu\text{m}$ ,  $20\mu\text{m}$ ,  $50\mu\text{m}$ ,  $100\mu\text{m}$ ,  $150\mu\text{m}$ , respectively  $200\mu\text{m}$ .

Photolithography process is a technological process that in optimum processing conditions produces normal distributed variations of the in plane dimensions [13, 14]. Therefore it is expected that each of the six data sets obtained by measurements has a normal distribution. This hypothesis is statistically tested. Since the mean and standard deviation values of the data sets

are unknown, the proper statistic test for verifying if the six data sets belong to a family of normal distributions is the Lilliefors test [15].

Lilliefors test is an adaptation of the Kolmogorov-Smirnov test [16] that verifies whether a data sample follows a normal distribution with known parameters (mean and standard deviation). The Lilliefors statistic is calculated by the same rule as the Kolmogorov-Smirnov statistic and it is equal to the maximum absolute value of the difference between the empiric distribution of the sample and the cumulative distribution function of the normal distribution with estimated mean and estimated variance:

$$LS = \max_x |F_{emp}(x) - CDF(x)| \quad (1)$$

The empiric distribution function of an identically distributed and independent data set  $(x_1, x_2, \dots, x_n)$  is calculated as follows [15]:

$$F_{emp}(x_i) = \frac{1}{n} \sum_{j=1}^n 1\{x_j \leq x_i\}, \quad \text{where } 1\{A\} = \begin{cases} 0, & \text{if } A \text{ is false} \\ 1, & \text{if } A \text{ is true} \end{cases} \quad (2)$$

To determine the cumulative distribution function, the mean and the variance of the normal distribution are estimated with the empiric mean, respectively with the empiric variance of the considered data set. If  $(x_1, x_2, \dots, x_n)$  is an identically distributed and independent data set, then the empiric mean and the empiric variance are calculated as follows [16]:

$$\mu_{emp} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3)$$

$$\sigma_{emp}^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \mu_{emp})^2 \quad (4)$$

The cumulative distribution function is in this case the repartition function of the normal distribution with parameters  $\mu_{emp}$  and  $\sigma_{emp}^2$  and has the expression:

$$F_{ref}(x) = \Phi\left(\frac{x - \mu_{emp}}{\sigma_{emp}}\right), \quad (5)$$

where  $\Phi$  is the Laplace function.

To determine the critical region of the Lilliefors test, the Lilliefors statistic is compared with the critical value corresponding to a certain significance level from the critical values table of the Lilliefors distribution. The mathematical software Matlab [17] has implemented a table with critical values for the Lilliefors test calculated using a Monte Carlo algorithm for data samples with volumes lower than 1000 and for significance levels between 0.001 and 0.5. To apply the Lilliefors test for the six data sets obtained from experimental measurements of the microfluidic test structures, it has been used the Matlab

predefined ‘lillietest’ function for a significance level of 0.01. The result showed that each of the six considered data sets has a normal distribution.

A supplementary verification of the precision of the photolithography process is done statistically by testing for each of the six considered data sets is the statistical mean of the data is equal to the designed value of the geometrical dimension of the microfluidic test structures. This is done by applying the t test [16] which tests the null hypothesis “the data become from a normal distribution with the mean equal to  $\mu_0$  and unknown variance”, versus the alternative “the data do not have the mean equal to  $\mu_0$ ”. Since the Lilliefors test showed that all the six considered data sets are normal distributed, all the necessary conditions for applying the t test are accomplished. The t statistic is calculated by the formula [16]:

$$t = \frac{\mu_{emp} - \mu_0}{\sqrt{\frac{\sigma_{emp}^2}{n}}}, \quad (6)$$

where  $\mu_{emp}$  is the empiric mean,  $\sigma_{emp}^2$  is the empiric variance,  $\mu_0$  is the designed value of the geometrical dimension and n is the volume of the tested data sample. The statistic t has a Student distribution of parameter n-1, which means that the critical value of the t test is determined from the table of the Student distribution for a significance level  $\alpha$  and n-1 degrees of freedom. For each of the six data samples, the t test returned the null hypothesis at a significance level of 0.01. This means that the statistical mean value of the measurements is equal to the deigned value of the dimensions of the test structures.

The next step of the statistical analysis is to determine if the data obtained from the measurements have the same statistic variance regardless of the designed value of the measured structure. This is done by applying a Bartlett test [15] of variance equality between various data samples. The Bartlett test compares the null hypothesis “the data have normal distributions with equal variances” versus the alternative “there are at least two data sets that do not have equal variances”. Since the Lilliefors test showed that all the data are normal distributed, all the necessary conditions for applying the Bartlett test are met. The Bartlett statistic is calculated using the formula [15]:

$$SB = \frac{(N - k) \ln s_p^2 - \sum_{i=1}^k (n_i - 1) \ln s_i^2}{1 + \frac{1}{3(k-1) \left( \sum_{i=1}^k \frac{1}{n_i - 1} - \frac{1}{N - k} \right)}}, \quad (7)$$

where  $k$  is the number of tested data sets (in the present case 6),  $n_i$ ,  $i=1..k$ , is the volume of the data set  $i$ ,  $s^2_i$ ,  $i=1..k$  is the empiric variance of the data set  $i$ ,

$$N = \sum_{i=1}^k n_i$$

is the total volume of the data, and

$$s_p^2 = \frac{1}{N-k} \sum_{i=1}^k (n_i - 1)s_i^2 \quad (8)$$

is an estimator of the common variance of the data samples.

The Bartlett statistic follows a  $\chi^2_{k-1}$  distribution [15]. Therefore, the critical value to which the Bartlett statistic has to be compared in order to perform the statistical test is determined from the table of the  $\chi^2$  distribution for  $k-1$  degrees of freedom and a significance level  $\alpha$ .

The statistical test Bartlett is implemented in the software program Matlab by the predefined function 'vartestn' [17]. This predefined function has been used to test whether the six considered data sets have equal variances. The result of the Bartlett test performed with Matlab is shown in figure 7.

Group Summary Table			
Group	Count	Mean	Std Dev
c010um	24	10.02	0.56956
c020um	30	20.077	0.5801
c050um	22	49.97	0.56835
c100um	27	99.957	0.52972
c150um	19	149.72	0.56775
c200um	21	199.96	0.49514
Pooled	143	81.712	0.55372
Bartlett's statistic		0.7695	
Degrees of freedom		5	
p-value		0.9789	

Fig. 7. The result of the Bartlett test applied using the predefined Matlab 'vartestn' function for the six considered data sets

The Bartlett statistic has the value  $SB=0.7695$ , while the critical value of the  $\chi^2$  distribution is  $\chi^2_{5,\alpha} = 1.61$ , for a significance level  $\alpha=0.01$ . The Bartlett statistic is lower in value than the critical value of the  $\chi^2$  distribution. This implies that the null hypothesis is accepted and the data sets have normal distributions with equal variances. The p value returned by the Matlab predefined 'vartestn' function indicates a probability of 97.89% of acceptance of the null hypothesis. The Bartlett test also indicates an estimate value of the common variance of the data samples  $s_p^2=0.5537$ .

The statistical analysis showed that the six data sets formed from the experimental measurements of the microfluidic test structures from the sample wafers are normal distributed with the same variance and the mean values equal to the corresponding designed values. All these conditions being met the measurement data can be reunited in a single global data set by calculating the difference between the values obtained from the measurements and the corresponding designed value. This global data set has a normal distribution with the mean value equal to 0 and the variance equal to the common variance of the initial six data sets,  $s^2=0.5537$  (fig. 8).

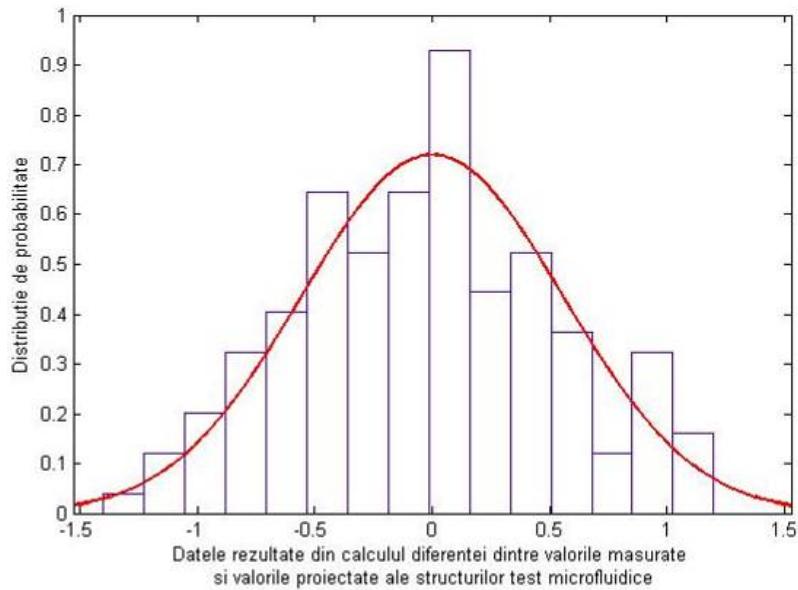


Fig. 8. The probability distribution and the histogram of the global data set obtained from the differences between the measurement values and the corresponding designed value

The defined global set is statistically modeled using a normal distributed random variable with mean  $\mu=0$  and variance  $\sigma^2=0.5537$ :

$$x = d_{measured} - d_{designed}, \quad (9)$$

$$x \sim N(\mu = 0, \sigma^2 = 0.5537) \quad (10)$$

In conclusion, the dispersion of the in plane geometrical dimensions of microfluidic structures fabricated by photolithography in SU-8 can be statistically modeled using a normal distributed random variable with mean  $\mu=0$  and variance  $\sigma^2=0.5537$  (fig. 9). Since the width of the microchannel is normally distributed, it results that 99.73% of the randomly generated values of the microchannel width

fall within 3 standard deviations ( $\mu \pm 3\sigma$ ). This corresponds to a  $\pm 1.6\%$  range of variation.

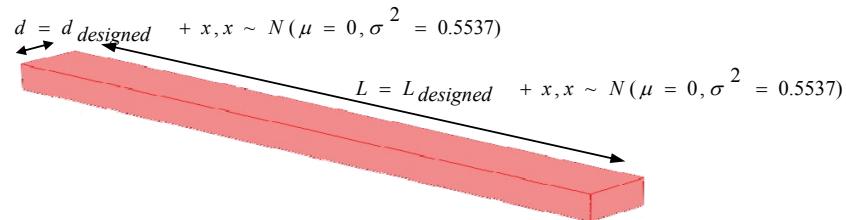


Fig. 9. The mathematical model of the variation of geometrical dimensions

### 5. Influence of the fabrication dispersion on the velocity of a fluid flowing through a rectangular microchannel

The main purpose of this paper is to determine a mathematical model for the inherent geometrical variations caused by the fabrication dispersion for one of the most common processes used for manufacturing microfluidic devices. This model is valid for any type of microfluidic device fabricated by SU-8 photolithography, regardless of its functionality or of the process in which the respective component is involved in. Such a model is necessary to be known in the design phase of a device, because it helps predict whether the considered fabrication process is appropriate for the desired application. Having this model available, it is possible to predict by simulation variation ranges of certain functional parameters of the designed device. In order to demonstrate this statement, in this section it is presented a study on the influence of the fabrication dispersion on the velocity of a fluid flowing through a SU-8 microchannel segment.

The microchannel is the most common and basic component of a microfluidic system. Simple microchannel structures are used as inlets in various types of microfluidic devices such as micropumps, micromixers, microfilters, droplet dispensers, microreactors, etc. or as connector elements between different components of a microfluidic system. Hence the velocity of a fluid flowing through a microchannel is an input parameter of the microfluidic component connected to the microchannel. Therefore it is important to have a good control of the fluid velocity through a microchannel, because variation in the fluid velocity can induce variations in the behaviour of the connected component. For example, variations in the velocities at the inlets of a micromixer can affect the diffusion

process, hence the general performance of the mixing process; variations of the velocities at the inlets of a droplet dispenser can induce variations in the volume of the generated droplets; etc.

The influence of the fabrication dispersion on the velocity of a fluid flowing through a microchannel segment with a rectangular cross section has been done by implementing a Monte Carlo simulation algorithm. Monte Carlo methods are computational algorithms that take as input random objects (random variables, random vectors, stochastic processes) and are used for computing numerical quantities (expectations, probabilities) in simulating physical and mathematical systems [3, 4]. The Monte Carlo algorithm implemented for the case study presented in this paper takes as random input a variable geometry of the simulated microchannel. The fabrication process considered for obtaining the microchannel is the SU-8 photolithography process; hence the statistical model used for generating the random input geometry is the model determined in the previous section for the SU-8 photolithography dispersion. An iteration of the Monte Carlo algorithm consists of a finite element simulation of the fluid flow through a 2D rectangular microchannel, with the geometry generated randomly from the dispersion model.

The fluid flow through a rectangular microchannel is modelled with the Navier – Stokes model for incompressible fluids [1], described by the equations:

$$\begin{cases} \rho \frac{\partial u}{\partial t} - \nabla \cdot [pI + \eta(\nabla u + (\nabla u)^T)] + \rho u \cdot \nabla u = 0 \\ \nabla \cdot u = 0 \end{cases} \quad (11)$$

where  $\rho$  is the fluid's density ( $\text{kg}/\text{m}^3$ ),  $u$  represents the velocity vector ( $\text{m}/\text{s}$ ),  $p$  is the pressure ( $\text{Pa}$ ),  $\eta$  is the dynamic viscosity ( $\text{Pa}\cdot\text{s}$ ) and  $I$  is the identity matrix. The boundary conditions for the Navier Stokes model are zero velocity at the wall interface, a driving pressure of 10Pa at the inlet and zero pressure at the outlet. The fluid that is flowing through the microchannel is water, with a density of  $10^3\text{kg}/\text{m}^3$  and a viscosity of  $10^{-3}\text{Pa}\cdot\text{s}$ . The deterministic simulation of the fluid flow through the 2D rectangular microchannel has been performed with the 2D Incompressible Navier-Stokes Application Mode of the MEMS module of the COMSOL simulation software [2]. The output parameter of each iteration is the value of the velocity field of the fluid along the median of the microchannel. A trial of 500 iterations is performed and a data set with the values of the output parameter is generated and analysed statistically.

In order obtain an intuitive image of the probability distribution of the results of the Monte Carlo simulation; the histogram of the obtained data set is plotted (figure 10). The histogram shows that an appropriate distribution for modelling the resulted velocity of the fluid along the median of the rectangular

microchannel is a normal distribution. The empirical mean of the fluid velocity data set is 1.507 mm/s and the empirical variance is 1.7032e-010.

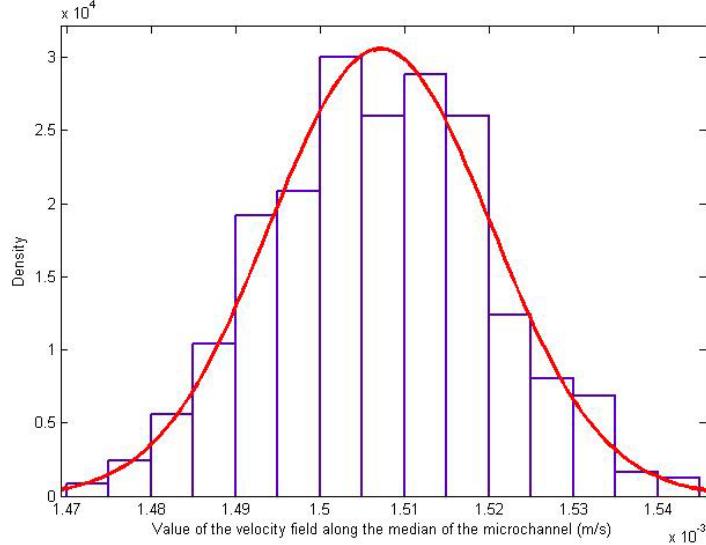


Fig. 10. Histogram of the results of the Monte Carlo simulation of the fluid flow through the 3D microchannel

A Lilliefors test has been applied to test if the fluid velocity through the microchannel can be modelled with a normal distribution of unknown parameters [3], as obtained from the histogram plot. The Lilliefors test is applied using the Matlab predefined function ‘lillietest’ for a 0.01 significance level [4]. The result of the statistical test showed that the analysed data set follows a normal distribution with the mean equal to the empirical mean (1.507 mm/s) and the variance equal to the empirical variance (1.7032e-010).

The finite element simulation has been performed also for the ideal case. The simulation result showed that the value of the velocity along the median of the microchannel with the dimensions equal to the designed values is 1.502mm/s.

It can be observed that the empirical mean of the velocity field along the median of the microchannel obtained from the Monte Carlo simulation is close to the value of the fluid velocity along the median of the microchannel obtained by the finite element simulation of the ideal geometry. Therefore, it has been tested if the value of the velocity obtained from the deterministic simulation is equal to the expected value of the fluid velocity. This has been done by applying a t-test, using the predefined Matlab function ‘ttest’ [4]. The test returned the null hypothesis at a 0.05 confidence level, which means that the value of the velocity of the fluid along the median of the microchannel varies symmetrically around the ideal value following a normal distribution.

The range of variation of the value of the fluid velocity along the microchannel median is determined using the tolerance interval method. The tolerance interval method can be applied, because the distribution of the fluid velocity is a normal distribution. The lower boundary of the velocity variation is 1.471mm/s and the upper boundary is 1.543mm/s. This corresponds to a range of variation of  $\pm 2.42\%$ .

#### 4. Conclusions

In this paper it is presented a mathematical model for the dispersion of the SU-8 photolithography process with application for microfluidic devices. The variation of geometrical dimensions as consequence of fabrication dispersion cannot be completely eliminated or controlled. Environmental factors, the human factor, variations of equipment parameters influence the fabrication process and lead to variations of geometrical dimensions of fabricated structures from the designed values. Therefore it is necessary to understand and model the fabrication dispersion before the design phase of a device. The mathematical model of the geometrical dimensions variation as a consequence of the fabrication dispersion is a useful instrument for the optimization of the design process of microfluidic devices. Expected variations of the geometrical dimensions can be taken into account from the design phase and this way, costly and time consuming experimental steps can be avoided.

The knowledge brought in by the developed model of the fabrication dispersion of the SU-8 photolithography process leads to the development of an improved design and helps save costly and time consuming experimental steps. The variation of geometrical dimensions as result of fabrication dispersion can be implemented in the modeling and simulation phase of a device design and help predict variations of the device performance. This model can be used in the modeling and simulation steps of the design of any microfluidic device realized by photolithography in SU-8 and also in the design optimization of SU-8 master structures for replication process. An important characteristic of the fabrication dispersion model presented in this paper is that it can be applied for any microfluidic device fabricated by SU-8 photolithography developed for any application. The end use of the fabricated device is not relevant from the point of view of the fabrication dispersion model; hence the model is universal in the sense that it can be used in simulations and optimizations of any microfluidic application.

In order to demonstrate how the developed model can be applied in a practical case, a Monte Carlo simulation has been implemented for determining the probability distribution and the ranges of variation of the velocity field of a fluid through a microchannel segment. The simulation showed how the deviations

of the geometrical parameters propagate through the model of fluid flow through a microchannel segment and generate deviations of the fluid velocity field. The results of the statistical analysis showed that the fluid velocity is following a normal distribution with the mean equal to the value determined from the deterministic finite element simulation. To a range of variation of  $\pm 1.6\%$  of the width it corresponds a range of variation of  $\pm 2.42\%$  of the fluid velocity. This result is important because the velocity of the fluid is a parameter that affects the performance of any continuous flow microfluidic device. The deviations of the velocity have to be taken into account in the design of microfluidic systems because they can propagate further to other functional parameters like concentration distribution of samples, diffusion coefficients, volumes of dispensed liquid droplets, etc. Without the knowledge acquired from the fabrication dispersion model, this estimation of the variation ranges of the fluid velocity through the microchannel would not be possible.

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