Glass microlens arrays for Shack-Hartmann wavefront sensors

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Abstract
Microlens arrays for Shack-Hartmann wavefront sensors were fabricated by field-assisted silver ion migration in glass. The theoretical model was made, which describes the dependence of the parameters of microlenses in matrix on technological process of lens fabrication. The technological regimes are selected, allowing to make microlens arrays with wide range of optical parameters for measuring various wavefront distortions.

Keywords: Microlens array, Shack-Hartmann wavefront sensor

1. Introduction
Shack-Hartmann sensors are used in optical systems, which include wavefront measurements. Sensor consists of a two-dimensional microlens array focusing on a CCD chip. Microlens arrays for Shack Hartmann wavefront sensors usually have long focal lengths and small lens apertures. Requirements for such microlens arrays are: equal focal lengths over the whole matrix, a small focal spot, close to diffraction limit, and high fill-factor.

The aim of work is the microlens arrays (for wavefront sensors) fabrication by field-assisted ion migration in glass [1].

2. Technological process modeling
The form of microlenses in the array has been preliminary modeled. The technology is based on field-assisted migration of silver in glass in AgNO₃+NaNO₃ salt melt. Technology is suitable to make various optical elements with step index profile.

The spatial distribution of Ag⁺ ion in glass was determined by solution of nonlinear diffusion equations, describing field-assisted migration of Ag⁺ ion in process of lens fabrication:

\[
\frac{\partial C_{Ag}}{\partial t} = \nabla \cdot \left( \frac{D_{Ag}}{1 - (1 - M)C_{Ag}} \nabla C_{Ag} \right) - \frac{qE}{f k T} \cdot \nabla C_{Ag},
\]

where \(C_{Ag}, D_{Ag}\) are the silver relative concentration and self-diffusion coefficient, \(M\) is the ratio of self-diffusion coefficients of silver and sodium, \(M = D_{Ag}/D_{Na}\), \(q, f, k, T\) is the electron charge, correlation factor, Boltzmann's constant and temperature in Kelvin, respectively.

Electric field is obtained as analytical solution of Laplace equation by conformal mapping [2]. For two-dimensional case:

\[
E_x - jE_y = j \frac{V}{W} \frac{K'(k)}{K'(q)} \sqrt{\frac{1 - sn^2(\beta u)}{sn^2(\zeta, k) - sn^2(\beta u)}},
\]
where $E_x, E_y$—cartesian components of electric field $\vec{E}(x, y)$, $W$—thickness of glass substrate, $V$ is the applied voltage across substrate in process of lens fabrication, $u = x + iy$ - the complex coordinate, $K$ is the complete elliptic integral, $K'(k) = K\left(\sqrt{1-k^2}\right)$. Parameter $k$ ($0<k<1$) is determined by the solution of equation
\[
\frac{K(k)}{K'(k)} = \frac{x_w + b_w}{2W},
\]
x$_w$ is the gap in mask and $b_w$ is the distance between adjacent gaps. The parameters $\beta, \zeta, q$ are determined as $\beta = 2K(k)/(x_w + b_w)$, $\zeta = K(k)x_w/(x_w + b_w)$, $q = k\text{sn}(\zeta, k)$, respectively, $\text{sn}$ – Jacobi elliptic function.

Eq. (1) with appropriate boundary conditions was solved by finite difference method with Crank-Nikolson implicit scheme, the concentration distribution $C_{Ag}(x,y)$ was determined. Mask parameters are: $x_w$ - 30 µm, $b_w$ - 120 µm, substrate thickness $W$ - 1 mm. Other parameters for modeling are: $D_{Ag} = 1.4 \times 10^{-15} \text{ m}^2/\text{s}$, $M = 0.72$, $T = 380^\circ \text{C}$, $f = 0.5$, $E = 25 \text{ V/mm}$.

The calculated microlens form (contours of concentration distribution) for diffusion time 1800 s is shown at Fig. 1. It can be seen that lenses have nearly semicircular form.

![Fig. 1. Microlens form in an array, produced by field assisted ion migration.](image)

Refractive index profile of lens cross section can be determined:

\[
n(x, y) = n_s + \Delta n \cdot C_{Ag}(x, y),
\]

where $n_s$ is the glass substrate index, $n_s = 1.515$ at wavelength 633, $\Delta n$ is the index increase, $\Delta n = 0.032$. Then we use beam propagation method to estimate microlens optical properties.

3. **Microlens array fabrication and measurements**

Microlenses were fabricated in optical glass (type K-8) substrate with dimensions 50×50×2 mm. Masking aluminum layer was evaporated in vacuum on one side of glass substrate. The metal thickness is 0.6 µm. In masking layer the matrix of circular holes (200×267) with 30 µm in diameters and period of 150 µm were etched by photolithography. At the opposite side of substrate the continuous aluminum layer was evaporated, serving as cathode. The prepared in such way substrate was contacted with salt melt AgNO$_3$ + NaNO$_3$. Migration of silver ions was stimulated by applying constant electric field to anode, dipped in salt melt and cathode, which has electrical contact with thin aluminum layer. Electric field was 25 V/mm. Ag$^+$ ions migration time was 30 minutes, process temperature - 380 $^\circ$C. After process ending, aluminum masking layer and thin-film cathode was removed by etching in 30% KOH solution. Then substrate was mechanically poled from deformed (former cathode) side.

The fragment of fabricated lens array photo is shown at Fig. 2.
At Fig. 3 microlens array vertical cross section photo is shown. Photo was made by scanning electron microscope JSM-7500F with energy dispersive X-ray spectrometer.

It can bee seen from Fig. 2 and Fig. 3, that fabricated microlenses have semispherical form and don’t have very high fill factor. Spatial distribution of silver ions in lens area is uniform, which is the feature of electric field-assisted ion migration. Accordingly, microlenses have step index profile.

The view of light intensity distribution at focal plane of lens array is shown at Fig. 4.

The fabricated arrays have diameter 125 µm, focal length 1.5 mm, focal spot diameter (Airy disk diameter) 19 µm. Optical parameters were measured at wavelength 633 µm. Fresnel number is equal to 4.1.

Application of this array in wavefront sensor with 8-bit CCD camera, which has 8 µm pixel size, allows to measure wavefront distortions with tilt dynamic range 8° (44 mrad) and tilt measurement sensitivity 20 µrad [3].

Additional microlens array annealing improves the lens quality and increase focal length. Microlens arrays were annealed at 450°C and, as a result, matrices with diameter nearly 150 µm, focal length 4.5 mm and focal spot diameter 49 µm were made. Fresnel number is equal to 2.

Array can be applied to measure wavefront distortions with tilt dynamic range 2° (11 mrad) and tilt measurement sensitivity 3 µrad, using the same CCD camera, as mentioned above.
4. **Conclusion**

Field-assisted ion migration was used to produce microlens array, consisting of 200×267 lenses with focal length 4.5 mm and focal spot diameter 49 µm. Array pitch is 150 µm. Array has high fill-factor - each lens has diameter 150 µm.

The advantages of microlens arrays, made by field-assisted ion migration, are that variations of diffusion process parameters and additional annealing, configuration of masking layers, and type of diffusing material result in forming lenses with different geometric dimensions and focal lengths.

The fabricated matrices allow to make Shack-Hartmann wavefront sensors with different sensitivity. Additionally, arrays have flat external surface, which makes it possible to get in close contact with various optical devices, including CCD chips.

**References**