Laser micro-machining using near-field optics

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Abstract
Solid immersion lenses (SIL) facilitate high numerical aperture (NA) and consequent sub-wavelength diffraction limited focusing in near-field optics based systems. Such systems are in commercial and research use for various applications including near-field scanning optical microscopy, ultra-high-density magneto-optic data storage and near-field nanolithography. Here, we present a novel manufacturing method using SIL-based near-field optics for laser-induced patterning on silicon wafers. The near-field effect of SILs was investigated by using hemispherical lenses made of three different materials (BK7, Sapphire, LaSFN9) to superfocus an incident Q-switched, 532 nm Nd:YAG laser beam transmitted through a focusing objective. This optical arrangement achieved a laser-processed feature resolution near the diffraction limit in air. Results of experiments that were conducted at various processing conditions to investigate the effects of varying incident laser power (with peak pulse power less than 1 W), pulse width, number of pulses and size of SIL on processed feature size and resolution are presented. Experimental results are compared with numerical simulations using the simplified model.

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1. Introduction

A near-field optical technique, using a new type of solid immersion lens (SIL), has been developed and applied to various areas, for example, high-density optical storage, near-field-scanning-optical-microscope probes, and photolithography. Solid immersion microscopy offers a method for achieving resolution below the diffraction limit in air with significantly higher optical throughput by focusing light through a high refractive-index SIL held close to a sample [1]. The minimum resolution of a focusing system is inversely proportional to numerical aperture (NA), where NA = n sin θ, θ is the maximum angle of incidence, and n is the index of refraction at the focal point. Light with vacuum wavelength λ can be focused by an aberration-free lens to a spot whose full width at half maximum (FWHM) is λ/2NA in the scalar diffraction limit, equivalent to Sparrow’s criterion for spatial resolution. In a medium of refractive index n, the effective wavelength is λ eff = λ/n and corresponding effective numerical aperture is NEff = n² sin θ. When a SIL is used, improvements in NA eff and spatial resolution are proportional to the refractive index of the SIL material. Fletcher et al. [1,2] demonstrated imaging in the infrared with a microfabricated SIL. Baba et al. [3] analyzed the aberrations and allowances for an aspheric error, a thickness error, and an air gap when using a hemispherical SIL for photoluminescence microscopy with submicron resolution beyond the diffraction limit. Terris et al. [4] developed and applied a SIL-based near-field optical technique for the writing and reading domains in a magneto-optic material. Song et al. [5] proposed the new concept of a SIL for high-density optical recording using the near-field recording technology.

In this paper, we propose a laser processing technique with spatial resolution beyond the diffraction limit in air using near-field optics. For this purpose, fundamental science needs to be studied for designing the near-field optical probe and for precisely controlling heat and mass transport during near-field laser processing. Our goal is to eventually develop a massively parallel optical direct-write manufacturing technique. Fig. 1 shows a schematic description of near-field laser-induced fabrication method envisioned by our study.

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2. Experimental procedures

SILs made of different materials (BK7, Sapphire, LaSFN9) with varying sizes were tested at different SIL-substrate distances in the 20–70 nm range using oxide pedestals that were grown and patterned onto 500 μm thick silicon wafers.

In our study, a TEM$_{oo}$ mode, frequency doubled, Q-switched Nd:YAG laser (Quantronix, Model 117, λ = 532 nm) was used and controlled by an external trigger input whose repetition rate and minimum pulse width are 50 kHz and 2 μs, respectively. Frequency doubling from 1064 nm to 532 nm was obtained by using a potassium titanium oxide phosphate (KTP) crystal. The beam stability is 4.0% RMS and beam divergence is 2.5 mrad. The 1.6 mm diameter TEM$_{oo}$ beam from the laser cavity was magnified 5 by a beam expander and then focused on a silicon wafer through a microfocusing objective that has a 4 μm theoretical spot size in air. The converging laser beam exiting from the objective was transmitted through a SIL placed on 50 nm SiO$_2$ nano-spacer patterns which were concluded to be optimal and created on top of the 500 μm thick silicon wafer as shown in Fig. 2.

When only a microfocus objective is used without a SIL, the numerical aperture of the system is the numerical aperture of the objective and is 0.4. However, the NA of the system is increased to $N_{\text{eff}} = 0.9237$ when a BK7 SIL with $n = 1.5196$ is interposed between the objective and the silicon wafer. Therefore, placing a BK7 SIL yields near diffraction limited performance with respect to focusing and a better spatial resolution with respect to processed features is expected. Furthermore, SILs made of materials with higher refractive index are expected to provide a larger $N_{\text{eff}}$ resulting in smaller focused near-field spot size and also smaller processed feature size. For this purpose, SILs made of sapphire ($n = 1.7718$, $N_{\text{eff}} = 1.2557$, 2 mm diameter) and LaSFN9 ($n = 1.8590$, $N_{\text{eff}} = 1.3824$, 1 mm diameter) were used. Fig. 3 shows the picture of our experimental setup and Fig. 4 is the magnified image of area around sample.

For analysis and characterization of our processed feature, Scanning electron microscopy (SEM) and Atomic force microscopy (AFM) were used.

3. Physical modeling

The processed feature was simulated using our one-dimensional heat transfer model [6,7] and the simplified model by Schwarz-Selinger et al. [8] to predict two-dimensional fluid flow driven by the inhomogeneous surface temperature from the results of one dimensional surface temperature and melt depth. These simulation results were compared with the experimental results.

Schwarz-Selinger et al. suggested energy density at the focal-plane of the objective lens as following:

$$F(r) = \frac{2E k^2}{\pi} \left[ \int_0^{a_0/w_0} \rho \exp(-\rho^2) J_0(kr\rho) \, d\rho \right]^2$$

(1)

$$k = \frac{2\pi w_0}{f\lambda}$$

(2)
where \( f \): focal length of an objective lens; \( J_0 \): zero-order Bessel function; \( w_0 \): 1/e² intensity radius of the Gaussian beam at the back-focal plane; \( a \): radius of the truncation aperture in the back-focal plane.

In our case, radius of the truncation aperture in the back-focal plane (\( a \)) equals 1/e² intensity radius of the Gaussian beam at the back-focal plane (\( w_0 \)).

They considered two limit cases according to the time scale of the laser pulse compared with the time scale for the diffusion of fluid momentum through the thickness of the melt. In the limit of a long laser pulse (\( \Delta t \gg h^2/\nu \), \( \Delta t \): laser pulse width, \( h \): melt depth, \( \nu \): kinematic viscosity), \( I \): the definition of an integrated temperature, \( \langle h^2 \rangle \): an average melt depth and consequent change in the morphology are as following:

\[
I = \int_{T_s > T_m} (T_s - T_m) \, dt \quad (3)
\]

\[
\langle h^2 \rangle I = \int_{T_s > T_m} h^2 (T_s - T_m) \, dt \quad (4)
\]

\[
\Delta z = -\frac{1}{2\eta r} \frac{\partial a}{\partial T} \left( r \frac{\partial \langle h^2 \rangle}{\partial r} \right) \quad (5)
\]

In the limit of a short laser pulse (\( \Delta t \ll h^2/\nu \))

\[
I = \int_{T_s > T_m} (T_s - T_m) \, dt \quad (6)
\]

\[
\langle h^2 \rangle = 2\nu \int_0^\infty \exp \left( -\frac{2\nu t}{h^2} \right) \, dt \quad (7)
\]

\[
\Delta z = -\frac{1}{2\eta r} \frac{\partial a}{\partial T} \left( r \frac{\partial \langle h^2 \rangle}{\partial r} \right) \quad (8)
\]

Here, it is assumed that lateral heat flow is negligible and, therefore, the dependence of \( I \) and \( \langle h^2 \rangle \) on the radial coordinate of fluid momentum through the thickness of the melt. In the limit of a long laser pulse (\( \Delta t \gg h^2/\nu \), \( \Delta t \): laser pulse width, \( h \): melt depth, \( \nu \): kinematic viscosity), \( I \): the definition of an integrated temperature, \( \langle h^2 \rangle \): an average melt depth and consequent change in the morphology are as following:
$r$ is given exclusively by the radial distribution of the energy density $F(r)$.

Integrated temperature $I$ and average melt depth $\langle h^2 \rangle$ were obtained by our one-dimensional heat transfer model with phase change. With this information, the change of morphology was computed using Mathematica (Wolfram Research) from the above equations.

4. Results and discussion

The results of several experiments that were conducted at various processing conditions to investigate the effects of varying incident laser power (with peak pulse power less than 1 W), pulse width, number of pulses and size of SIL on processed feature size and resolution are presented below.

Fig. 5a and b is SEM images of laser processing experiments conducted when single pulse at 20.4 mW peak pulse power and 2 μs pulse width is applied. Fig. 5a corresponds to the experiment conducted without a SIL while Fig. 5b represents the same experiment with a 2 mm diameter BK7 SIL. As can be seen, Fig. 5b shows a sharper laser processed feature due to a more focused laser spot than the one in Fig. 5a. There is a distinct central hole and overall feature size is bigger in Fig. 5b. This difference arises from the increased effective numerical aperture $NA_{eff} = 0.9237$ obtained by interposing the BK7 SIL between the microfocus objective and the silicon substrate, resulting in improved focusing of the laser and consequently finer spatial resolution.

Fig. 6a–c shows the SEM images of experiments conducted using a 2 mm BK7 SIL at different peak pulse power, while keeping all other experimental parameters fixed, i.e. 2 μs pulse width and single-shot pulse input. As the peak pulse power is increased from 15.3 mW up to 29.5 mW, a distinct central hole is created in the substrate. Its size and overall feature size are increased.

Fig. 7a and b illustrates the average diameter of the hole as a function of peak pulse power and number of pulses, respectively, keeping all other experimental conditions fixed. Three experiments were conducted at each setting. Fig. 7a shows that the diameter of the central hole is increased as peak pulse power is increased from 15.3 mW up to 29.5 mW, keeping pulse width, number of pulses, and SIL size fixed. Fig. 7b illustrates the results for 1, 3, or 5 pulses using a 2 mm BK7 SIL at 15.3 mW peak pulse power and 2 μs pulse width. The mean diameter of the laser machined central hole is proportional to the number of pulses exposed, keeping all other experimental parameters fixed.

Fig. 8a and b illustrates the effects of pulse width and SIL diameter, respectively on the mean diameter of the laser machined hole, keeping all other experimental conditions fixed. Fig. 8a shows the results of experiments that were conducted using a 2 mm BK7 SIL at 15.3 mW peak pulse power and
single-shot pulse with 2 µs, 4 µs and 6 µs pulse widths. From this plot, it can be observed that the mean diameter of the laser machined central hole is proportional to the pulse width. Fig. 8b shows the results of experiments conducted using BK7 SILs of 2 mm, 4 mm and 6 mm diameter at 15.3 mW peak pulse power and single-shot pulse with 2 µs pulse width. It is observed that the mean diameter of the laser machined central hole is inversely proportional to SIL diameter.

In particular, it should be noted from Figs. 7 and 8 that the mean hole diameter change is relatively small, respectively for 3 and 5 pulses, 4 µs and 6 µs, 4 mm and 6 mm SILs. These results lead us to believe that even smaller laser machined features and holes are possible by the optimal combination of these parameters. After using a few times at high power level, the SIL is damaged or some molten silicon is deposited on its surface. However, at the power level near the threshold value which is being investigated in our experiments, the SIL was rarely damaged or contaminated.

To obtain a larger NA_{eff} resulting in smaller focused spot size and also smaller processed feature size, we investigated the use of 2 mm diameter sapphire and 1 mm diameter LaSFN9 SILs having higher refractive indices than BK7. Fig. 9 shows the SEM and AFM images for experiments conducted using a 1 mm LaSFN9 SIL at 4.4 mW peak pulse power and single-shot pulse with 2 µs pulse width.

The AFM image in Fig. 9 shows a processed feature 2.5 µm wide and 228.0 nm high. In this case, the laser power is close to the threshold value. In comparison with the threshold results for BK7, it is of interest to note that smaller processed features and better feature definition were obtained for LaSFN9 while using...
less than half peak pulse power as that of BK7. This implies that larger NA_{eff} value of LaSFN9 results in smaller focused spot size, higher power density and consequently smaller processed feature. The LaSFN9 SIL also generated smaller and higher feature than that obtained with the sapphire SIL. This can be attributed to the higher refractive index and smaller diameter of the LaSFN9 SIL than the sapphire SIL.

Fig. 10 shows the simulated result using our one-dimensional heat transfer model and the simplified model by Schwarz-Selinger et al. for two different peak power levels with 2 μs pulse width. The simulated processed feature for the peak power with 45 mW is 1.0 μm wide and 170 nm high, while the feature is 1.0 μm and 110 nm high for the peak power with 43 mW. The power levels used in the simulations is 10× higher than those used in the experiment because SIL effect was not included in the simulations. However, the simulated result shows smaller and lower feature than that by the experiment shown in Fig. 9.

5. Conclusions

We conclude from our experimental results that the feature size obtainable by SIL-based near-field laser machining of silicon using a 532 nm Q-switched laser is proportional to the peak pulse power, number of pulses, and pulse width. The laser machined feature is also inversely proportional to SIL diameter with other parameters being same. Therefore, smaller laser machined features are attainable using a Q-switched laser with low peak pulse power, fewer pulses, shorter pulse width and smaller SIL diameter.

Furthermore, SILs made of materials with higher refractive indices can provide a larger NA_{eff} resulting in smaller near-field focused spot size and consequently smaller processed feature size.

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