Manipulation of heat-diffusion channel in laser thermal lithography

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Abstract: Laser thermal lithography is a good alternative method for forming small pattern feature size by taking advantage of the structural-change threshold effect of thermal lithography materials. In this work, the heat-diffusion channels of laser thermal lithography are first analyzed, and then we propose to manipulate the heat-diffusion channels by inserting thermal conduction layers in between channels. Heat-flow direction can be changed from the in-plane to the out-of-plane of the thermal lithography layer, which causes the size of the structural-change threshold region to become much smaller than the focused laser spot itself; thus, nanoscale marks can be obtained. Samples designated as “glass substrate/thermal conduction layer/thermal lithography layer (100 nm)/thermal conduction layer” are designed and prepared. Chalcogenide phase-change materials are used as thermal lithography layer, and Si is used as thermal conduction layer to manipulate heat-diffusion channels. Laser thermal lithography experiments are conducted on a home-made high-speed rotation direct laser writing setup with 488 nm laser wavelength and 0.90 numerical aperture of converging lens. The writing marks with 50–60 nm size are successfully obtained. The mark size is only about 1/13 of the focused laser spot, which is far smaller than that of the light diffraction limit spot of the direct laser writing setup. This work is useful for nanoscale fabrication and lithography by exploiting the far-field focusing light system.

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OCIS codes: (160.2900) Optical storage materials; (210.4810) Optical storage-recording materials; (220.3740) Lithography.

References and links


27. The thermal properties of silicon materials can be found in the following link: http://www.virginiasemi.com/pdf/Basic%20Mechanical%20and%20Thermal%20Properties%20of%20Silicon.pdf.


1. Introduction

Formation of nanometric patterns on surfaces and thin films is often carried out with advanced nanolithography techniques, such as electron beam ablation, nanoimprint, and local scanning probe microscopy methods. However, these techniques usually involve highly sophisticated procedures and require expensive equipment. Maskless direct laser writing has been a good choice for many applications in microelectronics and photonics. As far as nanometric patterns are concerned, the method suffers from fundamental resolving limit because of light diffraction. Therefore, light sources of short wavelength (\(\lambda\)) in deep ultraviolet and soft x-ray are increasingly adopted for forming fine structures. Nevertheless, maskless direct laser writing in the visible light wavelength remains attractive for many applications because it is easy to implement, and the cost is considerably lower than other lithography techniques. The writing process is in air, thus it entails easy operation and is suitable for large-scale production.
Maskless direct laser writing is generally thought to be a patterning technique that uses materials that are photosensitive. The pattern resolution is generally determined by the focused spot size. To improve the pattern resolution in maskless laser direct writing, a number of methods, such as ultrafast laser pulse-based multi-photon absorption lithography with $\lambda/10$ to $\lambda/20$ resolution [1, 2] and two-beam lithography [3–5], have been proposed.

Another alternative method is laser thermal lithography, which uses a single light beam with several milliwatts of power from a laser diode. The laser thermal lithography material absorbs the laser energy and is heated to a certain temperature, such as phase change or melting point, to form various patterns on the material surface. In laser thermal lithography, the thermal change of the material occurs over the whole area inside the laser beam spot, and the pattern whose size is the same as the processing laser beam spot size is formed. However, for heat-mode lithography, which is based on the manufacturing technique for optical discs, the thermally induced structural change of the material occurs only at the center of the laser beam spot because of threshold effect. A pattern whose size is smaller than the spot size can be formed [6–8].

Figure 1 illustrates the schematic principle of laser thermal lithography. A collimated Gaussian laser beam passes through a lens and is focused on a thermal lithography layer, which is directly deposited on a glass substrate. The thermal lithography layer absorbs the laser energy, and a cylinder heated volume is formed inside the thermal lithography layer with a thickness of tens of nanometers. In Fig. 1, $d$ is the focused spot size, $h$ is the thickness of thermal lithography layer, $T_{th}$ is the threshold temperature of thermally-induced structural change, $r$ is the radial coordinate, and “o” marks the spot center. The thermal lithographic region size becomes smaller than the resolution limit of the focused laser beam spot because of the thermally-induced threshold effect of structural change; thus, a fine pattern can be achieved using an inexpensive laser irradiation equipment. Furthermore, by using a high-speed rotating stage on which the processing sample is placed within the laser irradiation setup, below diffraction-limited large area and high-speed laser writing are possible [9–13].
developer accordingly [15–17]. Li et al. used AgInSbTe as thermal lithography material and obtained uniform and regular patterns [18, 19].

Actually, in laser thermal lithography, the pattern size is determined from two aspects: one is from heated region size and the other is from heat diffusion. The heated region size is mainly controlled by the laser beam spot size. For a given thermal lithography system, the laser beam spot size is fixed. The heated region size can be reduced using thermal lithography materials with nonlinear absorption characteristics, such as two-photon absorption and reverse saturation absorption [20, 21].

The other important factor in laser thermal lithography in determining the pattern resolution size is heat diffusion. Generally speaking, heat diffusion prevents the reduction of the lithographic region size, and the pattern feature size is usually larger than the estimated and expected size, which are especially obvious for thermal lithography that uses long laser pulse heating or slow sample movement speed and laser scanning rate. At the same time, for a given thermal lithography material and direct laser writing system, the lithographic pattern resolution is only restricted to a certain scale no matter how the experimental parameters such as writing power and speed are changed. The essence that the pattern feature size is larger than that of the estimated and expected stems from heat diffusion. However, this rule can be broken through manipulating the heat-diffusion channel, such that the pattern feature size can be further reduced down to nanoscale.

2. Theoretical analysis on heat-diffusion channel in laser thermal lithography

In this work, thermal conduction layer technique is proposed and used to manipulate the heat-diffusion channels to effectively decrease (or even eliminate) the disadvantageous influence of heat diffusion on the reduction of pattern feature size. The working principle is as follows: A collimated Gaussian laser beam is focused on the thermal lithography layer that has a thickness of $h$ and is directly deposited on the substrate. The focused spot diameter is marked as $d$. The thermal lithography layer absorbs the laser energy and is heated. An approximate cylinder heated volume is formed on the thermal lithography layer, as shown in Fig. 2, where the heated volume size is the same as the focused spot. The heated volume can be approximately calculated as $V = \frac{1}{4} \pi d^2 h$.

![Figure 2](image)

**Fig. 2.** Schematic of the heat diffusion channels for the heated volume.

Heat diffusion takes place when the temperature of the heated volume is higher than room temperature. Heat diffusions occur mainly along horizontal and perpendicular directions. In the horizontal direction, the heat diffusion is vertical to the side face of the heated volume and outward to the unheated region. It is called in-plane heat diffusion channel and marked as $D_{side}$. The side area of the heated volume can be approximately calculated as $S_{side} = \pi dh$. The perpendicular direction is called out-of-plane heat diffusion channel and marked as $D_{down}$. The perpendicular area of the heated volume can be approximately calculated as $S_{perpendicular} = \pi d^2 / 4$. 

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#221080 - $15.00 USD

Received 24 Sep 2014; revised 2 Dec 2014; accepted 15 Dec 2014; published 24 Dec 2014

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29 Dec 2014 | Vol. 22, No. 26 | DOI:10.1364/OE.22.032470 | OPTICS EXPRESS 32473
In the perpendicular direction, the heat diffusion is vertical to the surface of the thermal lithography layer and is called out-of-plane heat diffusion channel. The out-of-plane thermal diffusion channel is divided into two parts: one is upward to the air and marked as $D_{\text{up}}$ and the other is downward to the substrate and marked as $D_{\text{down}}$. In the perpendicular direction, the area of heat flow that passes through the heated volume in perpendicular direction is

$$S_{\text{perpendicular}} = \frac{\pi d^2}{4}$$

(2)

$S_{\text{perpendicular}}$ is the bottom (or top) area of the heated volume.

An analysis of the heat-diffusion channel would reveal that the heat quantity that propagates along the in-plane channel of the thermal lithography layer is proportional to the thermal conductivity $\sigma_{\text{litho}}$ of the thermal lithography layer, expressed as

$$Q_{D_{\text{side}}} \propto \sigma_{\text{litho}} S_{\text{side}}$$

(3)

The heat quantity that propagates along the out-of-plane channel of the thermal lithography layer and downward to the substrate is proportional to the thermal conductivity of the substrate ($\sigma_{\text{sub}}$), expressed as

$$Q_{D_{\text{down}}} \propto \sigma_{\text{sub}} S_{\text{perpendicular}}$$

(4)

The heat quantity that propagates along the out-of-plane channel of the thermal lithography layer and upward to the air is proportional to the thermal conductivity of the air ($\sigma_{\text{air}}$), expressed as

$$Q_{D_{\text{up}}} \propto \sigma_{\text{air}} S_{\text{perpendicular}}$$

(5)

The heat diffusion competition among these channels can be conveniently evaluated by comparing the heat quantity propagation between two channels.

An analysis of the heat-diffusion channels can be illustrated using an example. A Gaussian laser beam with a wavelength of $\lambda = 488 \text{ nm}$ is focused onto the thermal lithography layer with 100 nm thickness. The thermal lithography layer is directly deposited on the glass substrate. The numerical aperture (NA) of converging lens is set at 0.90. Hence, the sample structure is designated as “glass substrate/thermal lithography layer”, as shown in Fig. 1. The optical nonlinear absorption effect is not considered for the thermal lithography layer, but the linear absorption is considered. The heated region diameter $d$ should be approximately the same as the focused spot size. Thus, $d = 1.22 \lambda / \text{NA} = 662 \text{ nm}$. The height of the heated volume is $h = 100 \text{ nm}$. The thermal conductivity of the glass is $\sigma_{\text{glass}} = \sigma_{\text{sub}} = 1.09 \text{ W/ (m·K)}$. The chalcogenide phase-change material is usually used as optical and electrical storage materials due to large reflectance and electrical resistivity contrast between crystalline and amorphous states [22–24]. Here it is used as the thermal lithography layer [25]. The thermal conductivity of chalcogenide phase-change materials is about $\sigma_{\text{litho}} = 2.0 \text{ W/ (m·K)}$ [26]. The thermal conductivity of air is $\sigma_{\text{air}} = 0.024 \text{ W/ (m·K)}$.

The competition between $D_{\text{side}}$ and $D_{\text{down}}$ is expressed as

$$\eta_{D_{\text{side}}/D_{\text{down}}} = \frac{Q_{D_{\text{side}}}}{Q_{D_{\text{down}}}} = \frac{4h\sigma_{\text{litho}}}{d\sigma_{\text{sub}}}$$

(6)
The obtained $\eta_{\text{side/down}} = 1.11 > 1$ tells us that at the near of the bottom of the thermal lithography layer, the heat diffuses along the in-plane channel of the thermal lithography layer.

On the top surface of the thermal lithography, the heat can diffuse and dissipate into the air by thermal conduction, which includes heat transfer, heat convection, and thermal radiation. Heat transfer is only considered because the heat from the thermal lithography layer is initially transferred into the air layer near the thermal lithography layer through heat transfer and then dissipates into the atmospheric environment through heat convection.

The competition between $D_{\text{side}}$ and $D_{\text{up}}$ is written as

$$\eta_{D_{\text{side}}/D_{\text{up}}} = \frac{Q_{D_{\text{side}}}}{Q_{D_{\text{up}}}} = \frac{4h\sigma_{\text{side}}}{d \sigma_{\text{air}}}$$

(7)

The obtained $\eta_{\text{side/up}} = 50 \gg 1$ tells the heat at the top of the thermal lithography layer, mainly diffuses along the in-plane channel of the thermal lithography layer.

As shown in Fig. 2, the heat diffusion along the in-plane channel of the thermal lithography layer causes the pattern feature size to become large, whereas the heat diffusion along the out-of-plane channel of the thermal lithography layer leads to the pattern feature size reduction. Thus, whether at the bottom or on top of the thermal lithography layer, the heat diffusion along the in-plane channel of the thermal lithography layer causes the pattern feature size to become large.

To minimize the influence of heat diffusion on the pattern feature size, manipulation of the heat-diffusion channels is necessary. Hence, a method for manipulating the heat diffusion channels is proposed. The thermal conduction layers are inserted into the sample structure, and the heat-diffusion channels and directions are manipulated. As shown in Fig. 3, the sample structure is redesigned as “glass substrate/lower thermal conduction layer/thermal lithography layer/upper thermal conduction layer”, where the thermal conduction layers with large thermal conductivities are used to take the heat quantity along the out-of-plane channel of the thermal lithography layer. The thermal conduction layer needs to possess good light transmission at direct writing laser wavelength. Silicon (Si) is chosen as the thermal conduction layer material because of its large thermal conductivity of $\sigma_{\text{Si}} = 156 \text{ W/} (\text{m} \cdot \text{K})$ and low linear absorption coefficient ($\sim 10^6 / \text{m}$) [27]. The thickness of the material is set at 20 –100 nm.

Fig. 3. A sample structure with thermal conduction layers manipulating the heat-diffusion channels.
For the sample structure shown in Fig. 3, the heat-diffusion channels can be analyzed. The heat that propagates along the in-plane channel of the thermal lithography layer is the same as that in Fig. 2 and can be calculated by Eq. (3).

The heat quantity that propagates along the out-of-plane channel of the thermal lithography layer and downward (or upward) to the lower (or upper) thermal conduction layer is proportional to the thermal conductivity of the Si layer \( \sigma_{Si} \), expressed as

\[
Q_{D_{\perp \downarrow}} = Q_{D_{\perp \uparrow}} = \sigma_{Si} S_{\perp}\quad (8)
\]

The heat diffusion competition among these channels can be conveniently evaluated by comparing the heat quantity propagation between two channels. The competition among \( D_{\text{side}} \), \( D_{\perp \downarrow} \), and \( D_{\perp \uparrow} \) is expressed as

\[
\eta_{D_{\text{side}}/D_{\perp \downarrow}} = \frac{Q_{D_{\text{side}}}}{Q_{D_{\perp \downarrow}}} = \frac{Q_{D_{\text{side}}}}{Q_{D_{\perp \uparrow}}} = \frac{4h\sigma_{\text{ litho}}}{d\sigma_{Si}} = 0.008 \quad (9)
\]

\( \eta_{D_{\text{side}}/D_{\perp \downarrow}} = \eta_{D_{\text{side}}/D_{\perp \uparrow}} = 0.008 \ll 1 \) indicates that the heat diffusion along out-of-plane channels is dominant, and the heat quickly goes into the thermal conduction layer and concentrates on the center of the heated volume. Thus, the heat is transiently localized onto the apex of the heated region and goes quickly into the thermal conduction layer.

3. Experimental results and analysis

To check the proposed schematic principle, experiments were conducted in a home-made setup, where the laser wavelength is 488 nm and the NA of converging lens is 0.90, as shown in Fig. 4. The sample was placed at a vacuum-active worktable. The worktable was mounted at a high-speed rotation air-bearing spin stands. A light beam emitted from Ar + laser device was modulated into pulsed laser using acoustic optical modulator (AOM). The AOM was connected to a signal generator. An arbitrary wave form laser pulse can be obtained by tuning the signal generator. The laser pulse was then focused onto the surface of the sample by the converging lens, and the sample was fixed on the high-speed rotation air-bearing worktable by vacuum. The optical path, including the converging lens and AOM, was mounted on a linear motor with sub-micrometer movement accuracy.

In the laser thermal lithography experiment, the sample rotation speed was fixed at \( v = 10 \text{ m/s} \) and the laser pulse width was \( t_p = 50 \text{ ns} \). The chalcogenide phase change thin films \( \text{Sb}_{70}\text{Te}_{30} \) (or \( \text{AgInSbTe} \)) with a thickness of 100 nm were used as the thermal lithography layers. For \( \text{Sb}_{70}\text{Te}_{30} \) (or \( \text{AgInSbTe} \)) thin films, molten ablation can take place at a melting
point of about 500°C, which corresponds to a laser power density of about \(10^6 – 10^8\) W/m². Silicon was chosen as the thermal conduction layer material. Three kinds of sample structures were used to analyze the influence of heat-diffusion channel on the pattern feature size. The first was “glass substrate/thermal lithography layer (100 nm)”, which does not have any thermal conduction layer that would manipulate the heat-diffusion channel. The second was “glass substrate/thermal lithography layer (100 nm)/Si (20 nm)”, which has an upper thermal conduction layer that would manipulate the heat-diffusion channel of \(D_{\perp}\). The third was “glass substrate/Si (100 nm)/thermal lithography layer (100 nm)/Si (20 nm)”, which has both upper and lower thermal conduction layers that would synchronously manipulate the heat-diffusion channels of \(D_{\perp}\) and \(D_{\parallel}\), respectively. Si and Sb\(_{70}\)Te\(_{30}\) (or AgInSbTe) were prepared by radio frequency magnetron-controlled sputtering method.

Figure 5(a) gives the atomic force microscopy (AFM) observation of the optimized experimental results for “glass/thermal lithography layer (100 nm)” sample. A magnified image of Fig. 5(a) is presented in Fig. 5(b). The thermal lithography marks are hole structures, and the mark size is about 400 nm. The hole structures are formed by the molten-ablation effect. The thermal lithography layer absorbs the laser energy and is heated, and the molten-ablation holes occur when the temperature of the thermal lithography layer exceeds the melting point of about 500°C. The molten-ablation mark size of about 400 nm is smaller than the focused spot size of approximately 660 nm. Compared with the focused spot size, the reduction of molten-ablation mark size may result from the molten-ablation threshold effect.

The size of molten-ablation marks is reduced using the upper thermal conduction layer. Figure 6(a) shows the optimized experimental results obtained on the “glass/thermal lithography layer (100 nm)/the upper Si layer of 20 nm” sample, where the Si of 20 nm thickness is used as upper thermal conduction layer. Uniform thermal lithography marks are formed on the surface of the sample. A magnified image of Fig. 6(a) is presented in Fig. 6(b), and Fig. 6(c) shows a cross-section profile curve of the marks, highlighted with a grey line in Fig. 6(b). The marks are molten-ablation hole structures. The mark size is about 100 nm, and the mark depth is also about 100 nm. The mark size is obviously smaller than the focused spot size of 660 nm and also smaller than the mark size in Fig. 5, where no thermal conduction layer is used in the sample structure.
Let us analyze the reduction mechanism of the lithographic marks. There are some reports on the strong nonlinear effect of silicon thin films. The nonlinear absorption coefficient $\beta$ of silicon at 488 nm light wavelength is not reported, however, one can use $\beta$ at 405 nm light wavelength, which is close to the 488 nm light wavelength. Here $\alpha_0 \sim 5.0 \times 10^6 / m$, $\beta = -0.01236 m / W$ [28, 29]. The laser power is set at $P = 1 mW$, $I_0 = 2P / (\pi w_0^2) = 5.85 \times 10^6 W / m^2$ with $w_0 = d / 2 = 330 nm$. The thickness of the upper silicon layer is $h = 20 nm$. The super-resolved spot (transmitted from the upper silicon layer) can be calculated by [29]

$$I_i = I(r) \exp[-\alpha(r)h] \text{ with } \alpha(r) = \alpha_0 + \beta I(r), I(r) = I_0 \exp(-\frac{2r^2}{w_0^2})$$ (10)

Figure 7 gives the calculated results. The results indicate that the upper silicon layer can reduce the spot, the full width at half maximum of super-resolved spot is $0.8w_0$, and the incident spot is $1.18w_0$, accordingly. The super-resolved spot is reduced to about 68% of the incident spot size. However, the size of lithographic marks is reduced to only about 1/6 spot size, which is obviously smaller than the super-resolved spot size. Therefore, the reduction of lithographic mark size should be from other factors.

The nonlinear effect of the upper silicon layer can cause the formation of super-resolved spot. The super-resolved spot is directly coupled into the thermal lithography layer, and the thermal lithography layer is heated accordingly. Actually, the silicon is strongly absorbent in
the irradiation wavelength of 488nm, and the linear absorption coefficient is measured to be \( \alpha_0 \approx 5.0 \times 10^6 / \text{m} \), thus the silicon can also heat itself.

Let us compare the temperature rise of the upper silicon layer and thermal lithography layer. For laser pulse heating, if the heat loss can be ignored, the temperature rise at spot center region can be roughly calculated as [30]

\[
\Delta T = \frac{\alpha_0 I_B}{2\rho C} = \frac{D}{2\kappa} \alpha_0 I_B, \quad \text{with} \quad \frac{D}{2\kappa} = \frac{1}{2\rho C}
\]

where \( D \) is thermal diffusion coefficient, \( \kappa \) thermal conductivity, \( \rho \) density, and \( C \) heat capacity. For the upper silicon layer, \( D_{\text{Si}} = 42.7 \text{mm}^2 / \text{s} \), \( \kappa_{\text{Si}} = 156 \text{W} / (\text{m} \cdot \text{K}) \), \( \alpha_{\text{Si}} \approx 5.0 \times 10^6 / \text{m} \). For thermal lithography layer, the AgInSbTe phase change material is taken as an example, one has \( D_{\text{PC}} \approx 1.72 \text{mm}^2 / \text{s} \), \( \kappa_{\text{PC}} \approx 2.0 \text{W} / (\text{m} \cdot \text{K}) \), and \( \alpha_{\text{PC}} \approx 6.0 \times 10^7 / \text{m} \) [31].

For the upper silicon layer, the incident light central intensity is \( I_0 \). However, for phase change thermal lithography layer the central light intensity should be \( I_0 \times T_r \), where \( T_r \) is the transmittance of the upper silicon layer with a thickness of 20 nm. The experimental measurement indicates that \( T_r = 90\% \), which tells us that the most light energy passes through the upper silicon layer and is absorbed by the phase change thermal lithography layer. Let us roughly estimate the ratio of temperature rise between the upper silicon layer and phase change thermal lithography layer, which can be roughly estimated as

\[
\gamma_{\text{ratio}} = \frac{\Delta T_{\text{Si}}}{\Delta T_{\text{PC}}} = \frac{D_{\text{Si}}}{2\kappa_{\text{Si}}} \alpha_{\text{Si}} I_B = \frac{D_{\text{PC}}}{2\kappa_{\text{PC}}} \alpha_{\text{PC}} (I_0 \times T_r) = \frac{D_{\text{PC}}}{2\kappa_{\text{PC}}} \alpha_{\text{PC}} \times 90\% \approx 3.0\%
\]

The \( \gamma_{\text{ratio}} \approx 3.0\% \) indicates that the temperature rise at the upper silicon layer is far smaller than that at the phase change thermal lithography layer, thus the influence of temperature rise of the upper silicon layer on the temperature gradient of the sample can be ingored.

Actually, in our model, the key function of the upper silicon layer is guiding the heat flow along the heat-diffusion channel of \( D_{\text{side}} \) because \( \eta_{\text{side}} / D_{\text{side}} = 0.008 \ll 1 \). Thus, the mark size in Fig. 6 becomes smaller than that shown in Fig. 5 where \( \eta_{\text{side}} / D_{\text{side}} = 50 \gg 1 \) because no thermal conduction layer is used on the sample, and the heat mainly flows along the heat-diffusion channel of \( D_{\text{side}} \).

To further reduce the mark size, another heat-diffusion channel \( D_{\text{down}} \) was designed by inserting a lower thermal conduction layer between the substrate (glass) and the thermal lithography layer. The sample structure becomes “glass/ the lower Si layer of 100 nm/thermal lithography layer (100 nm)/the upper Si layer of 20 nm”. The optimized experimental results are shown in Fig. 8, where Si of 100 nm thickness and Si of 20 nm thickness are used as lower and upper thermal conduction layers, respectively. Figure 8(a) shows large area mark arrays, and the mark size is very small. Figure 8(b) is a magnified image of Fig. 8(a), and Fig. 8(c) is the cross-section profile curve of marks, highlighted with green line in Fig. 8(b). Based on Fig. 8, uniform marks are formed on the surface of “glass/Si (100 nm)/thermal lithography layer (100 nm)/Si (20 nm)” sample. The marks are hole structures, which stem from the molten-ablation effect of thermal lithography layer because of the laser pulse heating to the melting temperature of the thermal lithography materials. The mark depth is about...
20 – 30 nm, and the mark size is about 50 – 60 nm. The mark size is obviously smaller than those shown in Figs. 5 and 6. The mark size is also far smaller than the focused spot size and is only about 1/13 of the focused spot size. These results indicate that in Fig. 8, the upper and lower thermal conduction layers can produce heat-diffusion channels of $D_{\perp}$ and $D_{\parallel}$ and guide the heat flow along the out-of-plane channel of the thermal lithography layer because $\eta_{D_{\perp}}/\eta_{D_{\parallel}} = 0.008 \ll 1$. The heat flow along the out-of-plane channel of the thermal lithography layer can prevent the heat from diffusing to the in-plane channel of the thermal lithography layer. Thus, the heat can concentrate toward the center of the heated region, which is very useful for reducing the molten-ablation threshold region and obtaining mark size that is smaller than focused spot. Thus, nanoscale thermal lithography mark arrays are successfully realized in our experiments.

![AFM observation of nanoscale thermal lithography marks obtained on “glass/Si (100 nm)/thermal lithography layer (100 nm)/Si (20 nm)” sample structure: (a) lithography marks, (b) magnified marks, and (c) cross-section profile marked with green line in (b).](image)

Here it should be pointed out that the nonlinear effect of the upper silicon layer induced-super-resolution also contributes to the reduction of mark size, as shown in Fig. 7. However, the main contribution to the reduction of mark size is from the manipulation of heat-diffusion channel and phase change threshold effect. These were verified in [32], where AgInSbTe was used as phase change thermal lithography layer, silicon was used as the lower thermal conductive layer. The sample was designed as “thermal lithography layer (AgInSbTe)/the lower Si layer/glass substrate”. Using the laser writing setup with NA = 0.9 and $\lambda = 405$ nm, the lithographic mark size was about 70 nm, which was about 1/8 spot size. These indicate that the lower thermal conductive layer of silicon can make the lithography mark size reduce to below-diffraction-limit.

4. Conclusion

In summary, we proposed to manipulate the heat-diffusion channels by inserting thermal conduction layers in between channels, in the laser thermal lithography. The heat flow direction can be changed from the in-plane channel to the out-of-plane channel of the thermal lithography layer, which causes the molten-ablation threshold region size to become much smaller than the focused spot itself; thus, the nanoscale marks can be obtained accordingly. The samples “glass/Si (100 nm)/thermal lithography layer (100 nm)/Si (20 nm)” were designed and prepared, where chalcogenide phase-change materials were used as thermal lithography layer, and Si layers were used as thermal conduction layer to manipulate the heat-diffusion channels. The laser thermal lithography experiments were conducted on a homemade high-speed rotation direct laser writing setup with 488 nm laser wavelength and an NA = 0.90 of converging lens. The writing marks with a size of 50 – 60 nm were successfully obtained. The mark size is only about 1/13 of the focused spot and far smaller than the light diffraction limit of the direct laser writing setup.
Acknowledgments

This work was partially supported by the National Natural Science Foundation of China (Nos. 51172253 and 61137002) and the Key Program of the Science and Technology Commission of Shanghai (Grant No. 11jc1413300). The author expresses appreciation to Dr. Aihuan Dun and Hongren Shi for their help in laser thermal lithography experiments and AFM observation.