Optical Disk Mastering Using Optical Superresolution Technique

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(Received September 20, 2000; accepted for publication December 4, 2000)

A new laser lithography technique using the effect of optical superresolution can effectively reduce the exposed spot size on a photoresist layer, thus allowing disk mastering toward higher density using an existing light source and optics. A thin metallic mask layer deposited on the top of the photoresist layer is used to obtain a “below optical diffraction limit” linewidth on the photoresist layer. The feasibility of the laser lithography technique, as evaluated by simulation and experimental results, revealed that the linewidth on the photoresist layer could be shrunk by more than 50% of the diffraction limit of the optical system.

KEYWORDS: disk mastering, thermal-induced superresolution, lithography

1. Introduction

In conventional laser lithography, which is used to make optical master disks, the laser beam is directly illuminated on a photoresist (PR) layer, so the resulted exposed area or spot size is restricted by the law of diffraction and is \( \gamma/\lambda/\text{NA} \), where \( \gamma \) and \( \text{NA} \) are the laser wavelength and numerical aperture of the objective lens, respectively. To reduce the spot size, the obvious approaches are to reduce \( \lambda \) and to increase \( \text{NA} \). However, the absorption coefficient of the PR material depends on the wavelength of the light source. \( \text{NA} \) of the conventionally used objective lens of a laser beam recorder is 0.9 and the theoretical upper limit of \( \text{NA} \) is 1.0 in air. Thus, the two schemes for reducing the focused spot size either have some complications or result in limited performance. The aim of this study is to demonstrate applications of the effect of optical superresolution on laser beam writing to effectively reduce the spot size on the PR layer, thus, allowing disk mastering toward higher density using existing light source and optics.

2. Principle of Optical Superresolution

The mechanism of optical superresolution is ascribed to the refraction index of the metal film as a function of temperature and the Gaussian intensity distribution of the laser beam. By illuminating a metallic mask film with a focused laser beam, the melting region whose size is much smaller than the focused laser spot size can be well controlled. The refraction index of the melting region changes rapidly. Thus, under the influence of the shading effect caused by the melting region, the intensity distribution of the transmission light becomes narrower than that of the incident light and forms a “below-diffraction-limit” spot size.

3. Simulation Model

To simulate the influence of optical superresolution on the laser lithography process, we developed a computer program based on Dill et al.’s exposure model and Mack’s development model by taking the properties of the laser lithography process into account. In the simulation, \( \lambda \) of 442 nm, \( \text{NA} \) of 0.5, and a metallic mask film made of a GeTeSb digital versatile disk random access memory (DVD-RAM) recording layer are used.

4. Experiment

To evaluate the influence of optical superresolution caused by the mask layer, a line was laterally exposed by a laser-exposing machine on a specimen with the structure shown in Fig. 1. The parameters for the experiment are listed in Table I. Before development, the mask layer evaporated on the PR layer must be removed by an acid solution (HF : \( \text{H}_2\text{O}_2 \) : \( \text{H}_2\text{O} \) = 1 : 1 : 4) that can remove the indium mask film completely and does not destroy the PR layer. After development, the exposed region was removed and formed a linear groove.

5. Simulation Results

5.1 Exposure process

The computer program was developed to simulate the laser lithography processes with and without the mask layer. The exposure of the PR results in the conversion of the photoactive compound (PAC) at a rate proportional to the light intensity that is influenced by the optical superresolution caused by the mask film. The distributions of the PAC concentration after exposure are normalized so that 1 and 0 represent unexposed and completely exposed, respectively, as shown...
in Fig. 2. Figure 2(a) is the 3-Dimensional distribution of the PAC concentration without the mask layer. Because of the Gaussian intensity distribution of the laser beam and the standing-wave effect, the distribution of the PAC concentration shows the Gaussian distribution in the $r$ direction and the damping characteristic in the $z$ direction. Under the influence of optical superresolution due to the existence of the mask film on top of the PR, the intensity distribution of the laser beam is distorted. Thus, the distribution in the $r$ direction shown in Fig. 2(b) is different from that of the Gaussian.

### 5.2 Development process

In the development process, the PR film is removed using developer solution according to its exposure state. The cross-sectional views of the PR layer after development are shown in Fig. 4(a) for without a mask layer, Fig. 4(b) with a 5 nm mask layer, and Fig. 4(c) with a 10 nm mask layer. The black regions denote the residual PRs. It should be noted that the step profile on the slope of the sidewall is caused by the standing-wave effect, as the damping characteristic shown in Fig. 2. For the sake of simplicity, we define the spacing at the bottom and the half depth of the groove as $W_{\text{interface}}$ and linewidth, respectively, as shown in Fig. 3. In Fig. 4(a), $W_{\text{interface}}$ is about 2.1 $\mu$m without the mask layer, and the slope of the sidewall is about 25°. According to the modeling, if we designed the diameter of the melting regions formed on the 5 and 10 nm mask layers to be 0.7 $\times$ spot size and 0.4 $\times$ spot size respectively, the optical superresolution effect can be produced. Consequently, as the thickness of the mask layer increases from 0 to 10 nm, $W_{\text{interface}}$ shrinks from 2.1 to 1.3 $\mu$m with the same slope of the sidewall, as shown in Figs. 4(b) and 4(c). Because the slope does not vary with the shrinkage of $W_{\text{interface}}$, the linewidth decreasing with $W_{\text{interface}}$ reveals the effect of optical superresolution by the mask layer.

However, it is very difficult to measure and control the diameter of the melting region in real-time, so we examine the influences of the melting-region diameter and the thickness of the mask film on the profile of the PR layer for comparison with the experimental results. The relationships among the thickness of the mask film, the melting-region diameter, $W_{\text{interface}}$, and the slope of the sidewall are depicted in Fig. 5. The four dashed lines are the simulation results and represent the slope of the sidewall. The auxiliary solid lines a and b depict the influences of the mask film thickness and the melting-region diameter on the profile of the PR layer, respectively. By varying the thickness of the mask film and the melting-region diameter, we find that $W_{\text{interface}}$ is mainly affected by the mask film thickness, and the slope of the sidewall can be adjusted by the melting-region diameters without changing $W_{\text{interface}}$, as shown by the solid lines a and b. The simulated results shown in Fig. 5 indicate that both the absorption effect, caused by the increase of the mask film thickness, and the shading effect, caused by the formation of the
6. Experimental Results

To observe the relationship between the shrinkage of the linewidth and the thickness of the indium mask layer easily, a gradient indium film was evaporated on the top of the PR layer, as shown in Fig. 1. The experimental parameters and the results are shown in Table I and Fig. 6. As the thickness of indium film increases from 0 to 38 nm, the linewidth gradually shrinks from 2.5 \( \mu \)m, the limit of the laser-exposing machine, to 1.03 \( \mu \)m. To ensure that the reduction of the linewidth is actually caused by optical superresolution, we further increase the thickness of the indium mask film. When the thickness is 40 nm, the linewidth does not shrink anymore, but broadens, as shown in Fig. 7. This result does not agree with that caused by optical superresolution, as the indium film is too thick to be melted by the laser beam. As soon as the melting region cannot be formed, optical superresolution can no longer function, so it cannot cause the shrinkage of the linewidth. Experimental results demonstrate that the linewidth reduction can only be caused by the optical superresolution effect.

A scanning electron microscope (SEM) micrograph of the groove profile is shown in Fig. 8, where (a) is without an indium mask film, (b) is with a 7 nm indium mask film, and (c) is with a 30 nm indium mask film. Most notably, with the shrinkage of the linewidth, the fluctuation of line edges gradually increases from 100 to 300 nm; the measured values below diffraction limit melting region on the mask film, affect the slope of the line profiles. Moreover, the optical superresolution is a combination of both effects.
are listed in Table II. Because the shrinkage of the linewidth depends on the thickness of the indium mask film, the fluctuation must be related to the thickness of the indium mask film. As the thickness of the indium mask film increased from 15 to 36 nm, the grain size of the film was found to grow rapidly from 20 to about 100 nm, as shown in Fig. 9. In the melting state, the larger the grain of the film is, the rougher the edge of the melting region, as illustrated in Fig. 10. The sharpness of the line is mainly determined by the grain size of the indium mask film.

For comparison with the simulation results, we observe the cross-sectional profile of the PR layer, as shown in Fig. 11. When \( W_{\text{interface}} \) decreases from 2.1 to 1.7 \( \mu \text{m} \) as a result of the increase of the indium mask film thickness, the slope of the sidewall remains almost the same. However, as \( W_{\text{interface}} \) decreases from 1.7 to 1.368 \( \mu \text{m} \), the sidewall slope changes from 33° to 25°. On the basis of the simulation results shown in Fig. 5, we presume that the shrinkage of the linewidth is due to the absorption effect caused by the increase of the indium mask film thickness and that the change of the slope angle is a consequence of the failure to form an aperture in the thick indium mask film.

7. Conclusion

New laser lithography technology using the optical superresolution effect, which can decrease the exposed area of the PR layer, was demonstrated. From experimental results, it is evident that a linewidth of more than 50% less than the diffraction limit defined by the laser-exposing machine was achieved, which agreed with the simulation results. Because
the effect can be applied to shorter wavelengths, further reductions of linewidths are expected to be feasible when a shorter wavelength light source and higher NA optics are used in, for example, a laser beam recorder.

Acknowledgements

This work was partially supported by the National Council, the Republic of China under contract No. NSC. 88-2622-L009-002 and the “Photonics Science and Technology for Tera Era” Center of Excellence under contract No. 89-E-FA06-1-4.