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CONTACT THERMAL LITHOGRAPHY

A. Schmidt* **X. Chen and G. Chen**
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

ABSTRACT

Contact thermal lithography is a method for fabricating patterns based on thermal effects. In contrast to photolithography, where resolution is limited by the wavelength of light used in the exposure process, thermal lithography is limited by thermal diffusion. A traditional metal-glass photomask is brought into contact with a wafer coated with a thermally sensitive polymer. The mask-wafer combination is flashed briefly with high intensity light, causing the metal features to heat up and conduct heat locally to the polymer. The polymer cross-links due to the temperature rise and forms an image of the mask. Simple models are presented to analyze the heating process and select appropriate geometries and heating times. In addition, an experimental version of a contact thermal lithography system has been constructed. Early results from this system are presented, along with suggestions for future development.

INTRODUCTION

The resolution of traditional photolithography is limited to the order of the wavelength of light used to expose the pattern. In an effort to increase resolution, the semiconductor industry has moved to shorter wavelengths. Unfortunately, using shorter wavelengths adds complexity and therefore cost to the exposure tool. Individual fabrication tools, such as lithography steppers, have reached tens of millions of dollars, and complete modern fabrication facilities require investments of several billion dollars. It is therefore desirable to have a simple, inexpensive lithography technique capable of reproducing sub-micron features. Contact thermal lithography is a new method of pattern transfer that uses heat conduction. In contrast to photolithography, the resolution of thermal lithography is limited by thermal diffusion. Because the resolution limit is no longer tied to an optical wavelength, thermal lithography has the potential to match or improve the resolution of traditional lithography at lower cost.

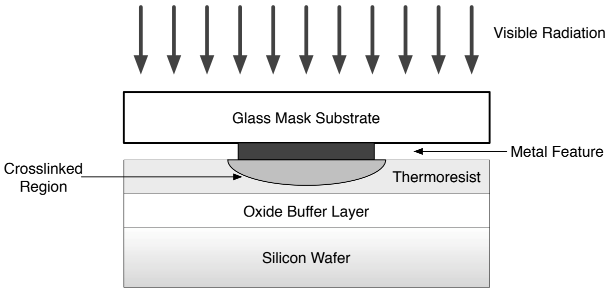

Figure 1. The basic contact thermal lithography process.

The basic thermal lithography process is straightforward. A mask consisting of metal patterned on glass is brought into contact with a wafer that has been coated with a thermally sensitive polymer referred to as thermoresist. The combination is flashed briefly with a high intensity laser of visible wavelength. The patterned metal features are strongly absorbing and rapidly heat up, while the optically transparent glass and polymer do not. Due to the short flash duration, the metal conducts heats only to the directly contacted polymer, causing local cross-linking. After the mask is removed, the wafer is developed in an appropriate solution, leaving behind only the cross-linked regions. Because the underlying wafer may be optically absorbing, a transparent thermal buffer layer such as SiO_2 is required between the wafer and the thermoresist. The process is illustrated in Fig. 1.

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*aarons@mit.edu

Unlike the family of lithography techniques based on imprinting a soft polymer with a stamp [1], thermal lithography requires only enough pressure to ensure contact between the mask and the wafer. In addition, it can reproduce truly arbitrary features without concern for the flowing and redistribution of an imprinting layer. The pattern mask itself is very similar to a traditional photolithography mask, consisting of metal features on a thin, transparent substrate. Masks with sub-micron features are typically produced with electron-beam lithography, which can be slow and expensive. Like all contact lithography techniques, thermal lithography faces challenges with regard to surface planarization and multi-layer alignment, but these issues are being dealt with by numerous research and commercial groups [2].

MODELING

The resolution limits of thermal lithography can be predicted using a transient conduction analysis of the contact region. It is first necessary to determine at what length scales the macroscopic heat diffusion is valid. In dielectric (non-conducting) solids, energy is primarily carried by phonons. Energy transport can accurately be modeled as a diffusion process when the phonon mean free path and the wavelength of the phonon itself are much smaller than the dimensions of the surrounding structure. If either of these conditions is not satisfied, energy transport should be modeled using ballistic transport theory or, if necessary, quantum mechanics. For typical materials such as polymethylmethacrylate (PMMA) or amorphous SiO_2, the mean free path is less than 1 nm for temperatures above 100 K [3]. At 300 K, a typical phonon wavelength is also on the order of 1 nm. Thus, for amorphous structures with dimensions of a few nanometers or more the diffusion model is adequate. Simple analytical modeling shows that heat propagates through the solid on the length scale of $\sqrt{\alpha t}$, where α is the thermal diffusivity. Finite element modeling reveals more details about lateral heat diffusion and temperature profiles in the solid. For an isotropic resist layer, when a temperature front has propagated through the resist, it will have propagated roughly an equal distance laterally. Thus resolution is limited to roughly the thickness of the resist layer. It is possible to spin-coat polymer layers that are as thin as 5 nm [4], indicating that thermal lithography has the potential to substantially improve upon traditional lithography.

EXPERIMENTAL SYSTEM

A basic CTL system has been built to demonstrate the feasibility of the method. Time constraints and a limited budget required that the system be made using easily obtainable parts and materials. The resulting apparatus and exposure method have very low throughput and are only capable of reproducing patterns on the order of a few microns. However, only a few basic changes would be necessary to increase both throughput and resolution.

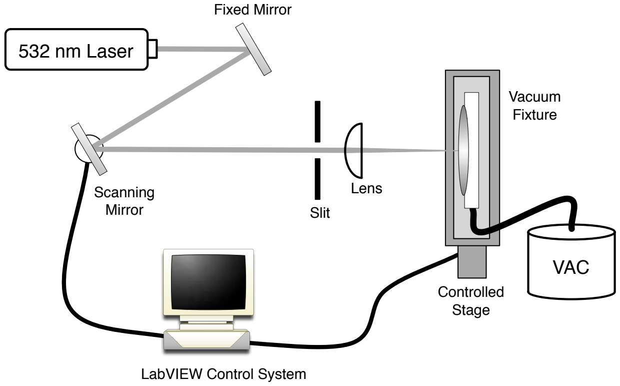

Figure 2. A schematic of a contact thermal lithography system.

A schematic of the system is shown in Fig. 2. An 8 W, continuous wave Nd:YAG laser at 532 nm laser serves as the light source. A small scanning mirror swings the beam through a wide arc. A thin slit positioned midway through the arc allows light through a focusing lens for a fraction of a second, and by varying the arc speed or slit width the pulse time can be controlled. The wafer and mask are placed in a vacuum chuck. A small pump is then used to remove the air between the mask and wafer. Because the mask substrate is thin (typically 1 mm or less), it is compliant and atmospheric pressure is sufficient to create intimate contact between mask and wafer. The chuck is held on a precise scanning stage used to maneuver the wafer during exposure. Using software written in the LabVIEW environment, the scanning mirror and positioning stage work together to expose small regions of a silicon wafer coated with a thermally sensitive polymer. For early testing, the resist layer used was AZ 5214-E (Clariant), a polymer normally used for image reversal lithography. This specific resist was first used for thermal pattern reproduction by Kuwahara, who used a laser to create nanoscale spots in a film [5]. The resist was diluted by 50% with a solvent (propylene glycol methyl ether acetate) and spin-coated to a thickness of approximately 500 nm.

RESULTS AND CONCLUSION

This arrangement was used to reproduce some basic patterns with a minimum feature size of 6 microns. Initially there were problems due to adhesion between the mask and resist layer that caused tearing of the patterned resist. This was traced to a non-uniform beam intensity. The problem was solved by using a different focusing lens to flatten the intensity profile. Fig. 3 shows a typical pattern produced with this system.

Additional work must be done before contact thermal lithography can become a viable nanomanufacturing technique. Next steps include testing the system with mask features significantly smaller than an optical wavelength and using thinner resist layers for improved resolution. This may require experimentation with polymers other than AZ 5214-E. Beyond this, it will be necessary to improve the throughput of the system. This will require the development more sophisticated optics and an improved method for positioning the beam on a wafer.

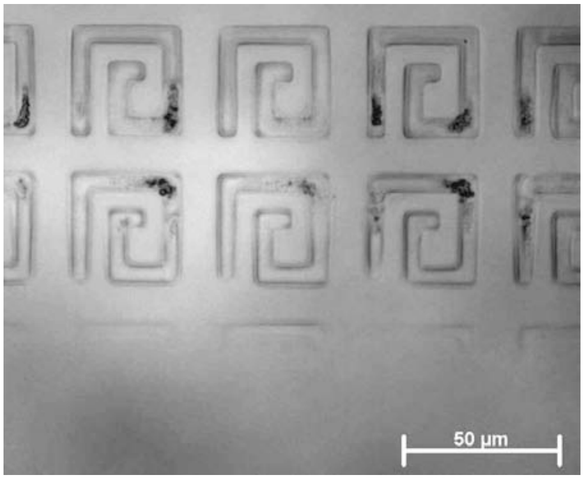

Figure 3. A pattern produced by thermal lithography. Minimum feature size is 6 μm.

ACKNOWLEDGMENT

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