ULTRASONIC MANIPULATION OF MICRON SIZE Bubbles IN NANO-LITHOGRAPHY

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ABSTRACT

In immersion nano-lithography, nanostructures are written on a wafer by illumination through a 200 µm thin water film that sits locally between the imaging lens and the wafer that scans horizontally at speeds up to 1 m/s. One of the important defect mechanisms in immersion lithography is the formation of air bubbles that enter the light path underneath the lens. Our combined numerical and experimental work shows that the micro-bubbles can be manipulated using ultrasonic waves, so that they can be prevented from reaching the light path during lithography. For our particular experimental conditions, micro-bubbles with radii between 25 and 100 µm can be stopped or deflected for scanning speeds up to at least 0.6 µm/s.

KEYWORDS: Ultrasound, micro-bubbles, immersion lithography, nano-lithography, acoustic forces

INTRODUCTION

Acoustically driven micro-bubbles can be used to advantage in micro-fluidic devices, for example for mixing [1], controlled drug delivery [2], surface cleaning [3], or poration of cell membranes [4]. Micro-fluidic devices can also be used to generate well-defined micro-bubbles, for example for use as contrast agents in medical imaging [5]. In nano-imaging industrial applications such as immersion lithography the presence of micro-bubbles poses an important risk since these may cause a distortion of nano-sized imaged structures on semiconductor wafers leading to failure of integrated circuits. Especially, the required high accuracies of next generation lithography tools demand avoidance of any micro-bubble entering the optical path in the thin liquid layer between the lens and the scanning wafer.

The approach being taken in this paper is to use ultrasound to prevent micro-bubbles from entering the light path during the imaging process. It is well known that micro-bubbles suspended in a liquid can be manipulated using ultrasound [6]. The special challenge in our case is the fact that we are dealing with bubbles attached to a substrate, and that the transportation speed of bubbles needs to be high because of the wafer scanning speed of up to 1 m/s. The effect of ultrasound and the optimal parameter set as to frequency and amplitude at this scale on sessile bubbles have not sufficiently been investigated previously.

EXPERIMENTAL SET-UP AND NUMERICAL MODEL

To test the feasibility of the concept, we conducted numerical simulations as well as basic experiments. The basic set-up shown in Figure 1 has been used to show in practice that micro-bubbles attached to a fast moving surface are prevented from moving into a defined area (such as the light path) by an ultrasonic pressure field. A distribution of micro-bubbles with radii between 25 and 100 µm is generated by ultrasonic transducer 1, and they attach to a glass slide positioned above the transducer. With a controlled velocity up to 0.6 m/s, the glass slide is moved over a second transducer generating an ultrasonic pressure field with frequency 1.7 MHz, and the effect on the micro-bubbles is observed in-situ using a high-speed camera mounted on a microscope. The experiment is successful when the micro-bubbles are stopped from moving with the slide and are kept steady in the acoustic field. The transducer-glass slide distance, i.e. the flying height FH, can be set between 100 and 600 µm. The photo on the right shows the glass slide and the circular ultrasonic transducer.

![Figure 1: Experimental set-up for investigation of ultrasonic manipulation of attached micro-bubbles. Left: schematic of the set-up; Right: photo of the glass slide and the ultrasonic transducer.](image-url)
The numerical simulations consisted of various steps. First, the acoustic pressure field generated by the transducer was computed by Finite Element Modeling using the Helmholtz equation including acoustic dissipation. Second, the transient acoustic Bjerknes forces acting on the micro-bubble was computed by solving the relevant Rayleigh-Plesset equation. Finally, the resulting micro-bubble velocity was determined by solving the momentum balance including added mass, drag, acoustic force, and hysteresis force. The spatial distribution of the acoustic pressure (and its gradient) was taken into account through an iterative routine.

RESULTS AND DISCUSSION

Figure 2 shows the result of calculations. Here, the micro-bubble radius is 50 μm, and the acoustic frequency is 1.7 MHz. The spacing between the transducer and the glass slide, i.e. the flying height FH, is either 600 or 200 μm. Figure 2 (b) shows that the bubble experiences a fluctuating pressure gradient as the glass slide scans in the horizontal direction. Due to the acoustic force acting on the bubble, the bubble can be stopped from moving as shown in figure 2 (c) for a 50 μm radius micro-bubble as the slide scans at 0.5 m/s. This means that the bubble is stopped from moving with the glass slide and kept steady in the ultrasonic field. This happens near the edge of the transducer. Figure 2 (d) shows that a 50 μm bubble can be stopped against moving with the glass slide at any scan speed, as long as the acoustic power of the transducer is large enough; the flying height is 600 μm. The flying height has a strong influence on the effect: this is indicated in figure 2 (e) showing that a 200 μm flying height requires a much lower acoustic power to stop the micro-bubbles at a given scan speed.

Figure 2: Results of numerical simulations. (a) Computed ultrasonic pressure field between transducer and glass slide. (b) Pressure gradient as seen by a micro-bubble as the glass slide scans horizontally. (c) Position of a 50 μm radius micro-bubble as a function of time as the slide scans at 0.5 m/s. (d) Map indicating the possibility to stop a 50 μm radius micro-bubble as a function of scan speed and acoustic power at FH= 600 μm; the same for FH=200 μm.

Figure 3 shows snapshots from high speed camera movies taken during the experiments, for various scan velocities and transducer input voltages (the acoustic power scales with input voltage). The flying height is 400 μm. The micro-bubble diameters range from 25 μm to 100 μm. The edge of the circular transducer can be seen as a white arc. If the input voltage is sufficiently high, for a given speed, the central area above the transducer is kept clear of micro-bubbles (V). All bubbles are stopped by the ultrasonic field near the edge of the transducer or deflected around the central area. If the input voltage is too low, the micro-bubbles are not stopped and move on with the glass slide (X). In an intermediate range, the micro-bubbles are only partly stopped or deflected (V). These results are consistent with the numerical simulations of Figure 2 (d).
Figure 3: Snapshots from high speed camera movies taken during the experiments for various scan speeds and at various input voltages for the ultrasonic transducer; flying height=400 μm. If the input voltage is large enough, micro-bubbles are stopped for any scan speed.

Figure 4 shows that the effect depends strongly on the flying height FH, as was also predicted by the model (see Figure 2 (e)). The scan speed is 0.2 m/s in all cases. For a certain input voltage, there is an optimal flying height for stopping or deflecting micro-bubbles. This effect can be compensated for by increasing the input voltage (hence acoustic power), or by changing the ultrasound frequency.

CONCLUSION
Both the experiments and the simulations show that micro-bubbles can be stopped from moving with the substrate to which they are attached, and are kept steady or deflected from a central region by the ultrasonic field with a carefully chosen parameter set. For our particular experimental conditions, micro-bubbles with radii between 25 and 100 μm can be stopped or deflected for scanning speeds up to at least 0.6 m/s. These proof-of-concept results indicate that ultrasound offers an effective option to prevent micro-bubble related defects in immersion lithography, and more generally that ultrasound provides an effective way to transport micro-bubbles across surfaces. The next steps are to move towards implementation of the method in a real immersion lithography machine, first by using the model to design and optimize the shape and frequency range of the transducer, and then by carrying out further experiments.

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