High-Speed, Low-Volume Inkjet and its Role in Jet and Flash™ Imprint Lithography

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Abstract

Imprint lithography is an effective technique for replication of nanoscale features. Jet and Flash™ Imprint Lithography (J-FIL™) uses field-by-field deposition and exposure of a low viscosity resist deposited by inkjet printing onto the substrate. The patterned mask is lowered into the fluid, where capillary action assists to flow the fluid into the relief patterns. Following the filling step, the resist is UV cured, the mask is removed, and a patterned resist is left on the substrate.

J-FIL™ is a technique, where the imprint technology provides the nanoscale pattern resolution while the inkjet technology contributes the throughput that is required for industrial applications. The drop volume and drop placement accuracy of the inkjet-printed resist is critical, allowing the volume to be distributed appropriately across the substrate surface to achieve a uniform target thickness and preventing non-filling of the relief patterns. With J- FIL™, it is possible to resolve 28 nm structures with residual layer thickness of 13 and 20 nm on 300 mm and 450 mm Si-wafers.

In this study, improvements during the filling step are explored for low droplet volumes at high ejection frequencies when using standard printheads with jetting performance of 12 kHz, <3 pL and modified printheads with jetting performance of 28 kHz, <2 pL.

Introduction

Nanoscale fabrication of microelectronic circuitry and devices poses a major challenge for lithography technologies. While the continual improvement of optical lithography using phase-shifting, offside illumination, two-photon effects, *etc...* enables ever smaller feature sizes, the generation of the radiation energy levels required appears to be reaching the limit. In addition, the cost of ownership for these lithography tools is very high, making this technology unattainable for smaller players in the industry. As a result, next generation lithography, such as imprint lithography, has come into focus to provide economical alternatives at high quality and reasonable throughput.

Nanoimprint lithography (NIL) is a nano molding technique, where a 1X master template is pressed into a resin, leaving behind the complement of its topography. Thermal nanoimprint employs temperatures beyond the glass transition of the polymer to be patterned at pressures as high as 1900 psi [1]. Ultraviolet (UV) imprint lithography in contrast operates at room temperature and pressures as low as 2 psi, which reduces template deformation and enables high fidelity at high throughput.

Figure 1 presents a simplified process overview of Jet and Flash™ Imprint Lithography as it is discussed in this contribution. In a first step, the substrate wafer is coated with a transfer layer and adhesion layer. A patterned, transparent fused

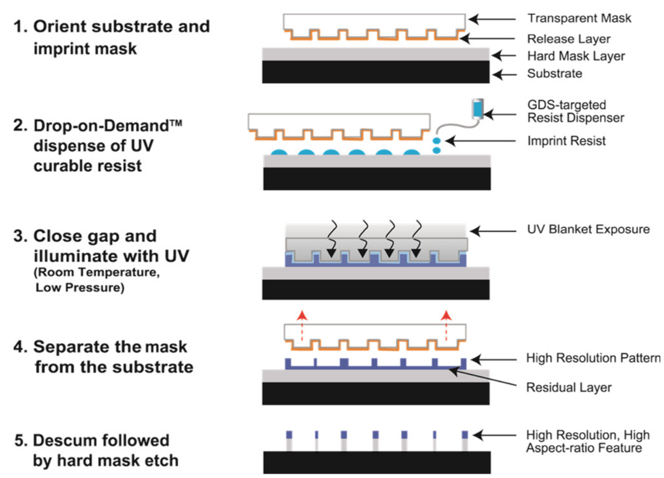

Figure 1: Simplified process flow for resist patterning using Jet and Flash™ Imprint Lithography (J-FIL™).

silica mask is used to perform field-by-field alignment, which enables accurate multi-layer patterning. A low viscosity resist is inkjet-printed onto the transfer layer, providing a feature density dependent pattern. Capillary forces fill the template topography after bringing the template in contact with the liquid resist. At this stage, nanoscale in-liquid alignment is possible to account for any deviations. Viscous forces resulting from the flow of the resist balance the capillary action and result in a residual layer between the template surface and transfer layer. This residual layer thickness (RLT) and the line-to-space ratio defines the fidelity of the imprint, and hence, the critical dimensions (CD) of the final processed pattern. The residual layer thickness is required to be thin and uniform across the substrate to provide optimum pattern transfer to the substrate. UV light crosslinks the resist and results in a low surface energy complement of the template. After separation of the mask and the substrate, the residual layer is removed by a CF_4/O_2 etch before transferring the pattern to generate high fidelity, high aspect ratio features. Recent reports show the possibility to resolve 28 nm structures with RLTs of 13 nm and 20 nm on large 300 mm and 450 mm substrates [2,3]. These small feature sizes are applicable for use in industrial applications requiring multi-tiered structures, such as CMOS and bit patterned media [4,5].

Throughput, as well as, defectivity is affected primarily by the fluid dynamics after the template has been brought into contact with the dispensed resist material. Influencing factors are imprint time, mask velocity and force applied, number and pitch of the resist droplets, volume of droplets, pinning of the liquid meniscus at high aspect ratio structures as well as template edges, air entrapment during spreading and the dissolution of the gas.

The total squeeze time, i.e. the time for the printed droplets to coalesce, forming a homogeneous film, and fill the features on the template can be divided into two different stages, a viscous timescale for the spreading of the droplets and a timescale for the dissolution of the entrapped gases [6]. The spreading time is controlled by the viscous forces within the fluid during flow and exhibits a dependency of

$$t_{\text{spread}} \propto \mu \frac{L^2}{RLT}$$

where μ is the resist viscosity, L is the distance between the dispensed resist droplets and RLT is the residual layer thickness. From this relationship, it is clear that the spreading time is optimized by using a low viscosity resist and a reduced distance between the droplets. The RLT is defined by the CD and etch requirements. Bearing in mind, the total volume of the resist filling the template and the volume incorporated in the RLT, low volume droplets at high resolutions are needed for this optimization. When considering only capillary and viscous forces, simulations showed that dividing the fluid volume into multiple smaller droplets decreases the imprint time by roughly two orders of magnitude [1].

The second stage of the imprint process is then governed by dissolution of the entrapped gases on a viscous timescale, when the pressure gradient at the liquid-gas interface is negligible; and a diffusion timescale, when the gradient across the liquid-gas interface becomes significant and viscous flow from the RLT is retarded [7]. In this stage, the trapped gas volume is dependent on the drop pattern arrangement on the wafer surface.

The control of the RLT alongside with complete filling of the structures is essential for low defectivity and high fidelity imprint. Varying the dispensed droplet pattern with respect to the pattern density on the template was shown to produce low RLT variations of 1.4 nm 3σ on a field of 22 x 33 mm^2 with low defectivity [2]. Evaporation changes the volume of the droplet as a function of time, and therefore, the local resist pattern volume at the onset of the imprinting step [8]. The droplet size and droplet pattern therefore needs to be optimized to take the evaporation into account. Evaporation effects on the resist volume can further be reduced by inkjet printing at high frequency and high substrate feed rate.

Experimental

Jetting experiments were carried out using a Xaar1001FF printhead, delivering nominal droplet volumes of 6 pL, and a Xaar1002AMp printhead delivering 1 to 3 pL droplet volume [9]. Laboratory jetting was carried out using either an in-house developed Evaluation Low Volume Ink System (ELVIS) [10] or Xaar Hydra supplied with additional temperature control through an external heat exchanger. On tool experiments were carried out using a proprietary ink system described elsewhere [11]. Proprietary production grade materials were supplied for conducting the experiments.

Droplet formation was studied using a stroboscopic setup. Droplet volumes were calculated from gravimetric measurements. Printing experiments were conducted on specifically designed J-FIL™ jetting stations, equipped with proper stages and imaging equipment required for the process, and on Imprio™ 300 and Imprio™ 450 lithography tools.

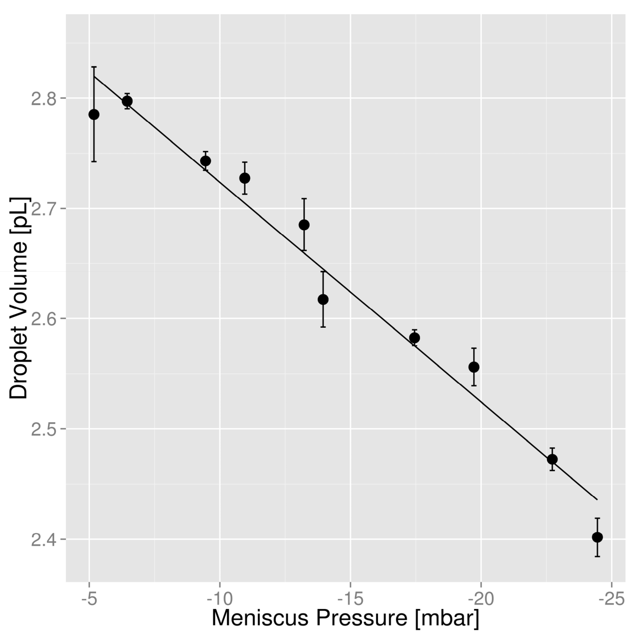

Figure 2: Influence of the meniscus pressure on the droplet volume, where air ingestion resulted for settings below -25 mbar [Xaar1001FF, Jetting temperature: 20 °C, Print frequency: 11.6 kHz].

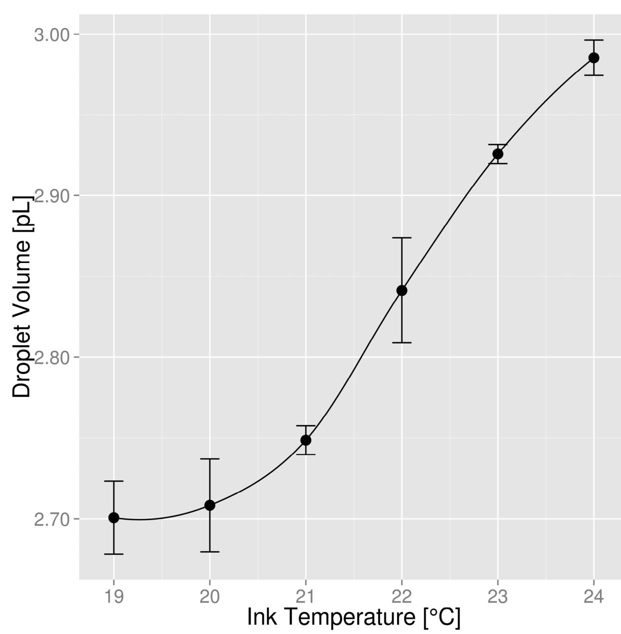

Figure 3: Influence of jetting temperature on the resulting droplet volume [Xaar1001FF, Jetting frequency: 11.6 kHz].

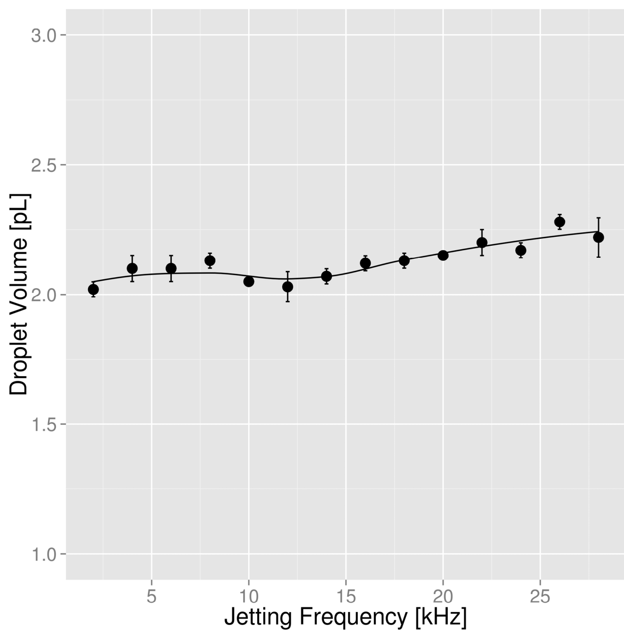

Figure 4: Volume as a function of frequency for a Xaar1002AMp [Resist temperature: 23 °C, 100% pattern density].

Results

In order to meet the low drop volume and high frequency requirements of the J-FIL™ process, an optimum inkjet printhead and waveform parameters were developed.

Acoustic firing can be employed to generate a time dependent pressure profile at the nozzle that minimizes the droplet volume without a major reduction in droplet velocity. A slightly reduced droplet velocity may be counteracted by adequate system design.

Furthermore, droplet volumes are strongly dependent on the meniscus pressure of the system as it changes the filling of the nozzle, and thereby, the acoustic impedance. Figure 2 shows the influence of the meniscus pressure at a jetting frequency of 11.6 kHz. It is interesting to note that the droplet velocity did not change significantly with hydrostatic pressure, which was most likely due to the variation in the differential pressure that resulted from relatively strong pressure drops along the tubes as the hydrostatic pressure was altered. Below a pressure level of -25 mbar, no stable conditions could be found as air was ingested through the nozzles.

Measurements were conducted to assess the sensitivity of the produced waveforms to variations in the printhead performance and to the fluid temperature. Initially, the timing of the waveform and the voltage to the actuator were varied and the influence on the print performance was monitored using volume and droplet velocity. The operational window was reduced due to the complexity of the waveform, which contained features for both reducing the drop volume and controlling crosstalk. When relaxing the requirements for droplet velocity and/or droplet volume, an even larger window could be obtained.

With the reduced operating window, the consistency of parameters external and internal to the print system had to be controlled extremely carefully. Figure 3 depicts the influence of temperature on the resulting droplet volume. Even small variations of the viscosity will change the acoustic performance of the printhead and result in a deviating droplet volume, which could induce variations in the residual layer thickness. Thermal control of the resist temperature is therefore not only necessary to minimize thermal drift in the imprint lithography tool, but also to ensure a constant droplet volume.

A major challenge was the generation of the reduced droplet volumes using the complex waveform at high frequency. The Xaar1001FF printhead geometry was optimized for ejection of greyscale droplets, which are formed by coalescing different numbers of subdrops. These subdrops are produced at a frequency of 42 kHz for 7 dpd (drops per dot) operation at 6 kHz line frequency. However, with this printhead, the time for dissipation of the residual energy in the channel was insufficient to allow for generation of highly repeatable and stable ejection of single drops at high frequencies.

Using the Xaar1002AMp printhead geometry, the performance was highly improved. The geometry change increases the acoustic impedance strongly and produces strong acoustic damping in the channel. Hence, the time for dissipation of the residual acoustic energy in the channel after each drop ejection was strongly decreased and allowed for more stable higher single droplet ejection frequencies. Figure 4 depicts the behavior of a Xaar1002AMp printhead as a function of frequency for a nominal 2 pL droplet volume. As the damping from the actuator design reduces the remaining energy in the channel, more simple waveforms could be applied and showed the depicted behavior. Only a slight linear increase could be observed, hinting at some in-channel crosstalk.

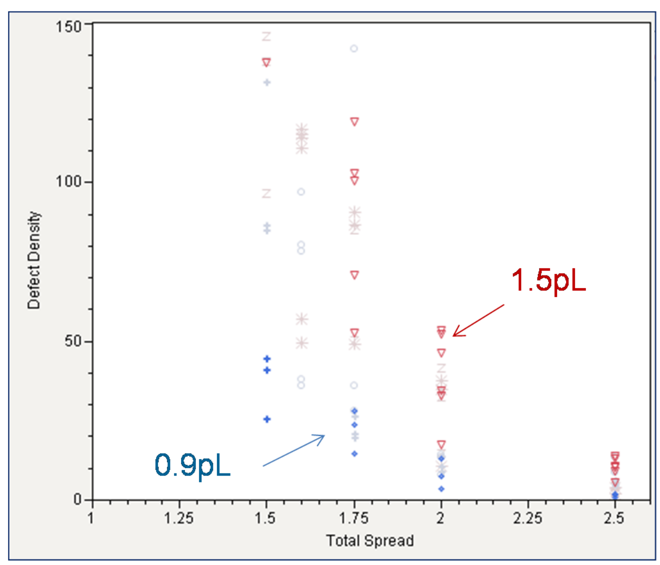

Figure 5: Xaar1002AMp demonstrates improvements in defectivity and total spread time for <2pL drop volumes [2].

As the drop volume is reduced for Jet and Flash™ Imprint Lithography, individual drops can be located closer together, reducing the amount of space and the travel distance between the drops. Figure 5 demonstrates the reduction in spread time and non-filling defectivity between a 0.9 pL vs. 1.5 pL droplet volume, which in turns improves the throughput and yield per wafer. In J-FIL™, the RLT is targeted and the droplet volume used must allow the drops to be arranged such that the mask patterned features are filled while maintaining the desired wafer throughput and preventing non-fill defects. Figure 6 shows that 1 pL droplet volume allows closer drop placement in X and Y pitch for a targeted 15 nm RLT of the desired mask. For larger drops, such as 3 pL, the droplets are placed farther from each other and there will be fewer droplets to utilize for targeting a 15nm RLT. These larger drop volumes have limited use and constraint the drop pattern layout for the imprint process.

Figure 7 provides an example of a J-FIL™ imprinted 300mm wafer using the Xaar1002AMp with 1 pL capabilities. Smaller drop volumes permit better process tuning when imprinting, but this is even more important when addressing imprint fields on the edge of the wafer. The edge imprints are called partial fields and the center fields are termed full fields. The 1 pL drop volume allows better distribution of the total volume across each individual field, where unique drop patterns are designed specifically for the field's geometry.

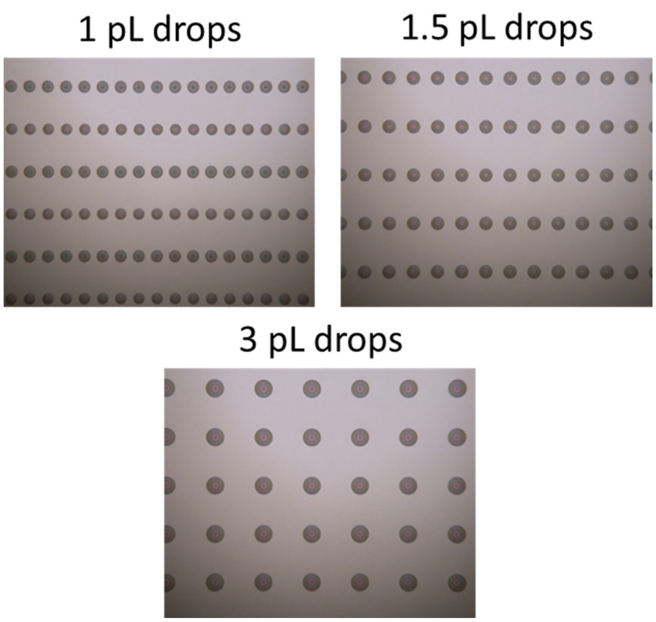

Figure 6: Closer drop placement obtained with smaller droplet volume, while maintaining the overall residual layer thickness requirement.

Conclusion

We have examined the positive impact of inkjet technology in the Jet and Flash™ Imprint Lithography process. With a high frequency and low drop volume printhead, the J-FIL™ process is significantly improved with regards to reduction in imprint time (high throughput) and good filling of the mask (low defectivity).

We have shown that droplet volume of a Xaar1001FF could be reduced by specific waveform design and a slight trade-off in droplet velocity, with a maximum jetting frequency of 11.6 kHz. The requirements for system optimization and control were shown to be rather high, as influences such as temperature variations strongly affects the ejected droplet volumes, and hence alter the performance of the overall process.

Using the Xaar1002AMp, consistent droplet ejection with much simpler waveforms was shown to be possible up to 30 kHz. The acoustic damping of the actuator design assists the dissipation of residual energy while providing lower nominal droplet volumes, thereby relieving the necessity for complex waveforms.

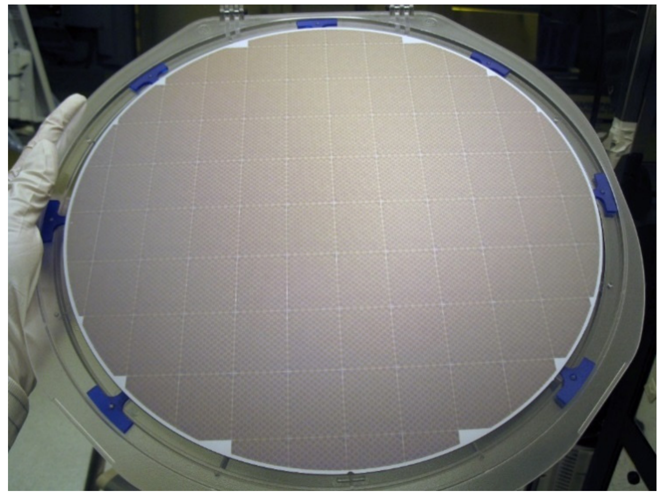

Figure 7: A fully imprinted 300mm wafer [2].

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Author Biography

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