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Large-Area, High-Resolution Lithography and Photoablation Systems for Microelectronics and Optoelectronics Fabrication

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Invited Paper

Abstract: An important requirement in the production of numerous microelectronic, optoelectronic, and microsystem devices is lithographic patterning on a large area with high image resolution and precise layer-to-layer alignment. Whereas for production of semiconductor devices, advances have been steadily made in steppers and other conventional lithography systems, the lithography requirements for the fabrication of large-format products, such as displays, multilayer circuits, and flexible electronics, are distinctly different, rendering various conventional lithography tools inadequate. These requirements and distinctions of large-area lithography are discussed. In the last several years, we have developed a new class of projection lithography systems that provide both high-resolution imaging and very large exposure area capability with high-precision alignment. The systems, using excimer laser sources, function as dual-mode, high-throughput production tools, capable of patterning in photoresists as well as photoablation in polymers, making them attractive for production of numerous large-format products, with feature sizes ranging from 15 μm to below 1 μm and substrate sizes ranging from 150 x 150 mm to 610 x 915 mm. We review the new lithography system technology, several completed systems, and demonstrated results.

Keywords: Lithography systems, projection imaging, seamless scanning, large-area exposure, photoablation, microelectronics, optoelectronics, displays, microelectromechanical systems.

A. INTRODUCTION

As advances in electronic systems with higher speeds, greater functionality, and higher densities continue to place greater demands on the design and manufacturing of microelectronic devices and modules, the demands in turn on the microelectronics production equipment continue to accelerate. Requirements of finer lines, pads, and vias are driving the need for lithography and photoablation equipment that can provide both high-resolution imaging capability and high-precision alignment performance. Simultaneously, the continued pressure on manufacturing costs requires that advances in equipment performance be coupled with *lower cost of ownership* through such key factors as throughput, yield, and minimum perturbation in well established, conventionally used materials and processes.

In the manufacturing of numerous microelectronic and optoelectronic products, such as displays, flexible circuits, wafer-level microelectronic packages, integrated optoelectronic panels, and microsystems, it is necessary to fabricate on a *single large substrate* millions of structures with feature sizes ranging from a few microns down to submicron. The substrate sizes vary, for example, from a few square inches for small microsystem modules to a few square *feet* for large-format displays, and the patterning system must provide the required resolution over the entire area with high processing throughput. The patterning technology used determines not only the ultimate performance of the product (e.g., pixel density in a display or interconnect density in a multilayer circuit), but also the economics of the entire manufacturing process. These performance and economic considerations at the module level ultimately influence the size and cost at the electronic system level.

<u>What is High Resolution?</u>

In the context of describing lithography equipment for a wide spectrum of electronic devices, it is important to discuss what "high resolution" means. While the smallest feature sizes are usually found in leading semiconductor ICs, this paper will try to dispel the widely held, but not entirely accurate, notion that progress in lithography is synonymous with advances being made in the VLSI semiconductor world, e.g., denser and denser memory chips. "High resolution" has different meanings in the context of different microelectronic and optoelectronic products. Thus, whereas in the world of displays the ability to pattern 1 μm features is considered high resolution, in the IC world even 0.25 μm lithography barely qualifies as leading-edge. Toward the other end of the spectrum, in the major areas of flexible electronics and printed circuit boards, the highest-density products are now beginning to use ~ 20 μm feature sizes. Thus, when discussing high resolution, whereas it is customary to focus on the minimum printable feature size, it is equally important to consider the *size of the substrate* over which the resolution is being achieved.

Many types of conventional exposure tools are currently used in the fabrication of electronic products, including: contact and proximity printers, single-field projection imaging systems, step-and-repeat tools, scanning projection printers, and focused-beam direct-write systems. All conventional lithography tools suffer from significant limitations, including one or more of the following: defect generation on the substrate, mask life degradation, limited substrate size capability, limited resolution, low throughput, stitching errors, poor yield, high system cost, poor opto-mechanical performance, and inability to drill vias in batch mode. In this paper, we focus on the requirements of large-format products, and describe how many of the above limitations have been overcome by a large-area laser projection lithography technology that we have developed in recent years.

Rationale for Large-Area Lithography

There are three primary drivers for the push in the development of new large-area lithography systems. The first is the recognition by the global large-format electronic product community of the fact that various conventional tools which have been the workhorses of the industry for two-to-four decades, such as contact printers and steppers, are, for large-area applications, at the end of their capabilities. A brief summary of the major conventional lithography tools used in the electronics industry and their shortcomings is given in Sec. B below. The second driver is the assessment by industry experts that these limitations are *fundamental*, meaning that periodic, evolutionary advances in the tools will no longer be sufficient to meet the demanding manufacturing requirements of large-format products. For example, it is recognized that, whereas numerous advances in contact printers have enabled them to now print ~ 25 μm features, they are unlikely to provide large-area lithography capability at the 5 μm level, and much less at 1 μm. Nor, even more critically, are they seen as ever being able to meet the corresponding alignment requirements. Steppers, on the other hand, may satisfy the resolution and alignment considerations, but not the large substrate size requirement.

Finally, and most importantly, it is increasingly being appreciated that the lithography requirements and challenges of large-format products are inherently different from those of ICs, and therefore, cannot be met efficiently by various attempts at modifying and adapting, for large-area lithography, the tools that were primarily designed for ICs. These distinctions can be discussed in the context of the following key performance criteria for large-area lithography: (a) resolution, (b) substrate size, (c) alignment precision, (d) depth of focus, and (e) cost of ownership, which is a composite figure of merit that takes into account throughput, yield, system price, operating costs, etc. In sec. B, we examine these criteria for the major conventional lithography tools in use.

We have developed a new class of projection lithography systems that provide both high-throughput, high-resolution resist patterning and dielectric via formation for fabrication of large-format, high-performance electronic products, eliminating the shortcomings of conventional imaging approaches.[1,2] An additional design feature of the new systems is their modularity, which provides equipment upgradability as well as choice of user-specified system configurations. These results are achieved with a unique, hexagonal seamless scanning technique and a single-planar stage configuration that provide both high optical and scanning efficiencies, and combine high-resolution imaging with very large exposure area capability. This paper describes the new lithography system technology, several completed patterning and via generation machines, and the experimental results. The new lithography systems are highly attractive for high-volume, cost-effective production of microelectronic products with feature sizes ranging from 15 μm to below 1 μm and substrate sizes ranging from 150 x 150 mm to 610 x 915 mm.

B. CONVENTIONAL EXPOSURE TECHNOLOGIES

Many types of conventional exposure tools are used in electronics production, and can be classified into three general categories: contact and proximity printing systems, various types of projection systems, and focused-beam direct-write systems. Here we summarize the limitations of these widely used technologies.[1] A contact printer holds the substrate in hard contact with the mask which is illuminated with a high-intensity lamp to transfer the mask pattern to the substrate. In a proximity system a uniform gap is maintained between the mask and the substrate. Major limitations of contact printing are defect generation on the substrate, low yields, mask life degradation, poor alignment capability, and poor ‘effective depth of focus’ (i.e., poor tolerance of substrate or mask aplanarity, requiring long vacuum pull-down times). Proximity printers also suffer from many of these limitations, with the additional problem of feature size variation due to mask-substrate gap nonuniformity. Furthermore, for via formation, photoablation with contact or proximity exposure is not possible due to the need for removal of the ablated dielectric material.

In a single-field projection tool, the image field of the lens is designed to accommodate the entire substrate. While being economical, such systems are limited by the fundamental trade-off between the desired resolution and the largest substrate they can image. In a step-and-repeat system the total substrate area to be patterned is broken up into several segments which are imaged one at a time by stepping the substrate from one segment to the next.(3) For IC lithography such segmenting is acceptable since the wafer is a periodic array of repeating small patterns (the ICs) which do not need to be aligned with each other with high accuracy. However, for large-format applications the full pattern is not a repetition of separated small patterns; therefore, lack of precise alignment between adjacent segments produces ‘stitching errors,’ leading to decreased yields. In addition, stepping increases overhead time, which significantly lowers the exposure throughput a stepper can deliver.

Among scanning projection tools, many different systems using a variety of illumination and imaging approaches are available from several manufacturers.(4) Such scanners, although capable of very good resolution and somewhat better exposure throughput than steppers, are primarily designed for IC production, and therefore, are incapable of handling the substrate sizes needed for large-format products. These scanners are also extremely expensive. Lower-cost, Dyson-type projection scanners have poor functional performance mechanically and suffer from low optical efficiency leading to low throughput. Additionally, all existing scanners lack modularity and upgradability, and do not provide via-generation capability.

A direct-write system uses a focused ultraviolet laser, electron, or ion beam in a raster scanning fashion to expose the substrate.(5,6) Since transfer of the pattern information by such tools takes place in a slow, pixel-by-pixel serial mode, typical substrate exposure times can range from a few minutes to several hours, depending upon the resolution and the complexity of the pattern data. Direct-write systems, therefore, are most suitable for applications such as mask fabrication, repair, and prototyping, and highly unattractive for cost-effective volume manufacturing of large-format electronic modules.

C. LARGE-AREA LITHOGRAPHY TECHNOLOGY WITH LASER PROJECTION IMAGING

In this section we describe a large-area lithography technology that combines laser projection imaging with efficient optomechanical techniques and systems. The resulting lithography system technology we have developed(1,2,7) provides the following capabilities:

- High-resolution projection imaging — minimum feature size (lines/spaces and holes) from 15 µm to below 1 µm
- Large-area substrate capability — easily configurable for panels of any size up to 610 x 915 mm
- High exposure speed — < 20 sec exposure time for 460 x 610 mm size panels
- Precise alignment — layer-to-layer or mask-to-panel alignment down to ~ 1/4th of resolution (e.g., 2.5 µm for 10 µm features and 0.25 µm for 1 µm features)

These performance features are achieved with a unique, hexagonal seamless scanning projection technique and a single-planar x-y stage configuration that provide superior optical and scanning efficiencies, and combine high-resolution, large-area imaging with high-precision alignment capability. We have built and installed several production systems and demonstrated their performance using conventional photoresists and polymeric dielectrics. An example of a dual-function system that provides both lithography and photoablation capabilities on large areas is shown in Fig. 1.

The core technology developed for the Anvik large-area lithography systems is schematically illustrated in Fig. 2. The panel and the mask (sometimes also called the reticle, artwork, or phototool) are rigidly mounted on a single-planar scanning stage that is capable of moving them *synchronously* in both x- and y-directions. The illumination system comprises a UV excimer laser light source and a beam-processing optical system. The exposure wavelength may be selected from several choices available from different excimer lasers, including XeF (351 nm), XeCl (308 nm), KrF (248 nm), ArF (193 nm), and F_2 (157 nm). Of these, the 351 nm wavelength from the XeF laser is ideally suited for imaging conventional photoresists designed for mercury arc lamp exposure, whereas the 248 and 193 nm wavelengths are chosen for deep-UV lithography. For photoablation, the most commonly used excimer laser wavelength is 308 nm; however, the 351, 248, and 193 nm wavelengths are also widely used. Irrespective of the UV wavelength chosen, the laser emits no infrared or other unwanted radiation. The beam-processing system illuminates the mask from below (through a cutout in the stage) in a uniform, hexagon-shaped illumination region that is typically 50 mm in size (vertex-to-vertex).

Fig. 1. An Anvik large-area, dual-function, projection lithography and photoablation system. The Model shown, 2150 SXE, uses a 308 nm XeCl excimer laser.

The mask pattern within the illuminated hexagonal region is imaged on to the panel by a unit-magnification projection lens through a folded image path. The projection lens, the illumination system, and all other optical components are stationary, as are all the light rays. The sole moving component is the single-planar stage, which is scanned in a serpentine fashion in the x-y plane so that the following sequence of events takes place: the mask and panel scan in unison along the x-axis across their respective hexagonal illumination regions; the stage moves them along y by an amount equal to the effective scan width (typically 35-40 mm; shown as w in Fig. 3); the mask and panel scan again along x (but in the opposite direction); they again move laterally by w along y; and the process is repeated until the entire panel is imaged. The hexagonal illumination configuration ensures that the whole exposure is completely seamless and uniform.

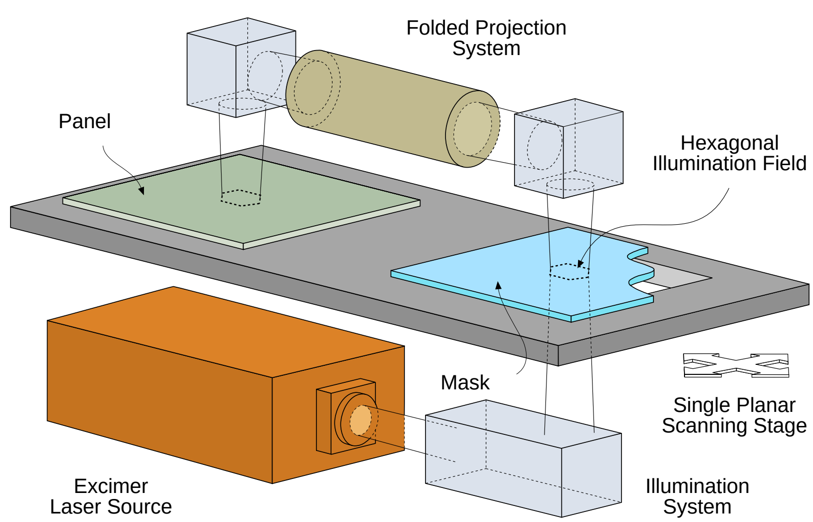

Fig. 2. Illustration of large-area, high-resolution projection lithography technology, showing scanning with a planar stage and hexagonal beam.

Figure 3 illustrates how seamless exposure is obtained by complementary overlap between adjacent hexagonal scans. The effective scan width is the scan-to-scan pitch, given by $w = 1.5\ l_h$, where l_h is the hexagon side length. Since the *time-integrated* exposure dose delivered by each hexagonal scan has a trapezoidal profile, the complementary overlap between adjacent trapezoidal dose profiles, as shown in the figure, results in a cumulative exposure dose from all scans that is totally seamless and uniform across the entire board.

Absence of Stitching Errors

To examine the seamlessness of the exposure, we may ask, (a) how precise does the positional overlap between the scans have to be, (b) how does an error in the lateral stage displacement from one scan to the next affect imaging and exposure uniformity, and (c) how does the effect of such an error compare to the stitching errors in a stepper? We note that in a stepper, any misregistration between adjacent segments on the substrate will cause stitching errors, whereas in this large-area lithography technology, since the mask and substrate never move *relative* to each other, there are *no* image stitching errors. We next examine the exposure dose stitching errors.

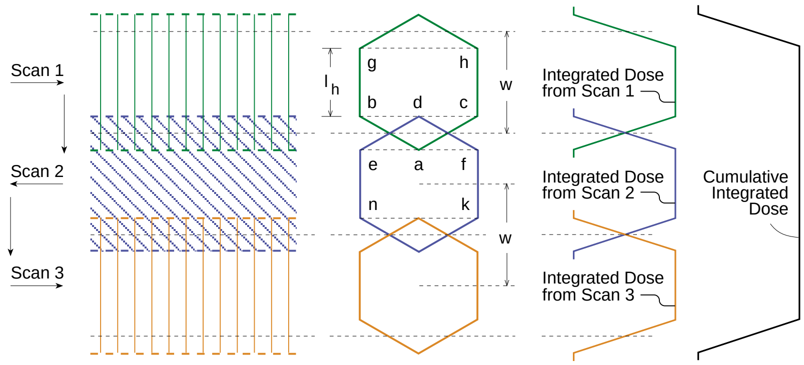

Fig. 3. The seamless scanning exposure mechanism. Adjacent hexagonal scans overlap partially, giving complimentary dose profiles. Integrated doses from successive scans produce uniform exposure over whole panel.

In a stepper, Fig. 4(a) shows how the exposure segments should butt exactly next to each other in the ideal situation. When there is a misregistration, the adjacent segments will either have a gap between them [Fig. 4(b)], leading to a *100%* underexposure in the gap region, or an overlap [Fig. 4(c)], leading to a *100%* overexposure. Such stitching errors are undesirable in many applications; for example, they result in noticeable defects in the rows or columns of a display. In contrast, in the large-area seamless system, the same magnitude of misregistration results in a totally negligible variation in the cumulative intensity profile. Any such variation can be readily estimated: it is the same fraction of the average intensity as the misregistration is of the hexagonal halfwidth, i.e., well under 1 part in 10^4. It can thus be said that the seamless scanning lithography system is free of stitching errors.

Thus, the large-area lithography technology described here makes it possible to obtain the desired resolution by selecting a projection lens of a suitable numerical aperture, and deliver that resolution over very large substrate areas efficiently by the technique of hexagonal seamless scanning. Note also that, since the mask and substrate are mounted rigidly on a single planar stage, issues concerning relative mask-substrate movements during imaging are eliminated. Another key advantage that is significant in keeping the system's cost-of-ownership low is its modular design — the main subsystems, including the illumination module, the imaging module and the stage module, are integrated in a mutually non-interfering manner. This important and unique feature permits not only choice of different user-specified system configurations, but also future upgradability of the systems as products migrate from one generation to the next.

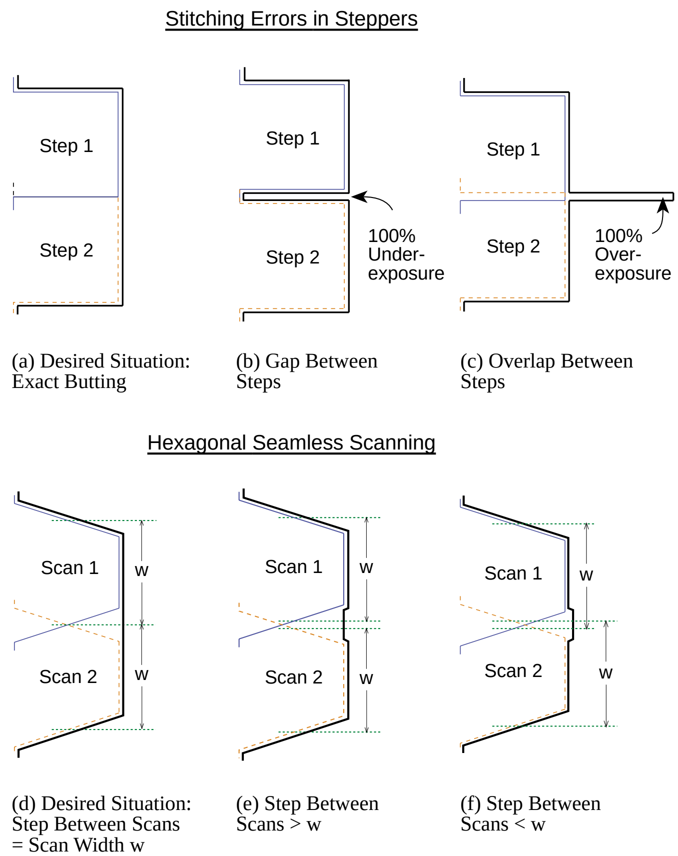

Fig. 4. Comparison between a stepper and a large-area, seamless scanning system for effect of misregistration between adjacent exposure regions, illustrating stitching errors in the stepper and uniform exposure in the seamless system.

D. SYSTEM DESCRIPTION

Now we provide an overview of the design parameters, both optical and mechanical, for several representative lithography systems that we have designed and built for patterning in various photoresists as well as via generation in dielectric polymers for fabrication of displays, flexible circuits, wafer-level microelectronic packages, integrated optoelectronic panels, and microsystems. We also provide examples of the different hardware subsystems that have been incorporated in building various systems. The overall design specifications of one of our systems, the 1-µm-resolution Model 1010 SDE, are shown in Table 1.

Table 1. Design and performance specifications of the large-area Anvik Model 1010 SDE projection lithography system for displays and microelectronics.

Large-Area Lithography System Specifications	
Imaging Technique	Seamless scanning projection
Resolution	1 µm
Projection System	1:1 magnification refractive lens
Numerical Aperture	0.174 (*f* / 2.87)
Depth of Focus	8 µm
Panel Exposure Area	200 x 250 mm
Exposure Source	KrF excimer laser
Exposure Wavelength	248.4 nm, line-narrowed
Alignment Precision	± 0.25 µm
Alignment System	Automatic
Panel & Mask Handling	Automatic
Exposure Throughput	120 panels / hr

The exposure source in most of our systems is an excimer laser; however, a mercury arc lamp may also be used when desirable. We have designed and built systems using a number of different excimer laser wavelengths — e.g., 248 nm, 308 nm, and 351 nm — as well as the *i*-line (365 nm) of the Hg lamp. For all applications, the excimer laser is the preferred source for a variety of reasons. In resist lithography, the excimer laser sources provides significantly greater throughput than a Hg lamp. In addition, for submicron imaging, the 248 nm KrF laser and the 193 nm ArF laser are highly desirable due to their ability to provide very-narrow-bandwidth, short-wavelength radiation. For via generation in interlayer dielectrics such as polyimide, the high fluence requirements necessitate the use of an excimer laser. The Hg lamp as a light source is considered only when a low-cost, low-throughput system is desired.

The beam from the light source is processed and relayed by a beam delivery system that transforms the input beam of any shape and intensity profile into a beam of hexagonal cross-section with a uniform transverse spatial profile. The output of the homogenizer, which serves as the effective emission plane, is imaged by a condenser system on to the mask mounted on the single-planar stage. The portion of the mask illuminated by the uniform, hexagonal beam is imaged by the projection system on to the substrate held on the same stage.

The projection assembly in all of our seamless scanning lithography systems is a unit-magnification, refractive imaging system. Its numerical aperture (NA) is designed to produce the specified resolution. For example, for the Model 1010 SDE, the projection system has an NA of 0.174, which provides a minimum printable feature size of 1 µm at the exposure wavelength of 248 nm. Other system models have resolution specifications from 0.5 µm to 15 µm, with the corresponding projection lens NAs ranging from 0.35 (for λ = 248 nm) to 0.0144 (for λ = 351 nm). The image field diameter of the projection lens is also determined by optical engineering considerations based on the resolution. As an example, for the Model 2100 SPE, which has a resolution of 10 µm, the field diameter of the lens is 50 mm, which enables *simultaneous* imaging of over 16 million pixels of 10 µm size. In throughput, this illustrates the fundamental, dramatic superiority of projection imaging over direct writing in which pixels are exposed serially.

The single-planar stage system is an air-bearing x-y scanning stage. Its travel ranges are designed to meet the panel size specifications, and can vary, based on the target applications, from 150 x 150 mm to 610 x 915 mm. The stage can scan in either direction at speeds up to 500 mm/sec. It holds the mask and the panel side-by-side, horizontally, in the *same* plane, which minimizes a variety of performance-limiting errors (e.g., Abbé and flexure) found in the stage designs used in some other lithography tools. The stage utilizes an optical encoder to provide position and velocity control, which is fully integrated with the system control software and, like the excimer laser, is run from the system computer.

Finally, all of our systems incorporate a high-precision, optical alignment system which is designed to be able to align the mask and panel rapidly and automatically to within a specified alignment tolerance. Such an alignment capability is necessary for layer-to-layer alignment in a multilayer circuit and for front-to-back alignment in a dual-sided panel. It is a rule of thumb in the industry that a suitable value for the alignment specification should be ~ 25% of the minimum feature size. Thus, for example, our 10-μm-resolution system (Model 2100 SPE) has an alignment precision of ± 2.5 μm, whereas the Model 1010 SDE, with its 1 μm resolution, has an alignment specification of ± 0.25 μm. The automatic alignment system consists of an optical metrology system and a fine-positioning system. The optical metrology system is used to determine the relative locations of the mask and substrate with respect to the projection system. Depending upon the desired precision, the optical metrology system incorporates some or all of the following subsystems: CCD cameras, pattern recognition software, confocal microscope(s), and a laser interferometer system. The position information for the mask and substrate is processed by the system computer and sent to a Fine Positioning and Alignment System (FiPAS), which imparts a relative x-y-θ correction in the position of the substrate with respect to the mask, bringing the two in the desired alignment. As previously emphasized, the high-precision alignment capability of our systems is an important advantage over other large-area exposure tools.

E. SYSTEM PERFORMANCE: DEMONSTRATED RESULTS

The large-area lithography technology described in the preceding sections has been fully demonstrated on several systems that are now in use in commercial and military production of large-format microelectronic and optoelectronic devices. In this section we provide examples of the results demonstrated on some of the lithography and photoablation systems. The exposures were made in several widely used photoresists and polymers, of both liquid and dry-film types, in various thicknesses, applied on several different substrates, both rigid and flexible. The results we have selected demonstrate the capabilities of these systems for production of high-resolution displays, wafer-level microelectronic products, and high-density multilayer circuits.

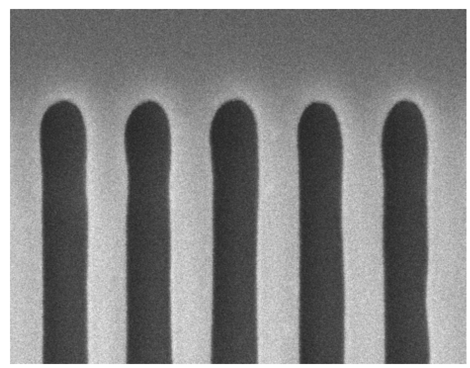

Fig. 5. Exposure showing 1 μm lines and spaces imaged on a large-area, deep-UV projection lithography system having a 248 nm excimer laser source.

Figure 5 shows results obtained on a large-area, deep-UV lithography system, the Model 1010 SDE. The light source in this system is a line-narrowed KrF excimer laser operating at 248.4 nm. The imaging system is a 0.174 NA projection lens consisting of all fused silica elements. The SEM in Fig. 5 shows images of 1 μm lines and spaces exposed in a 1 μm thick negative-tone deep-UV photoresist. The system has an 8 μm depth of focus and is capable of handling substrate sizes up to 200 x 250 mm, making it attractive for patterning high-resolution displays, both flat-panel and flexible, as well as various microsystems and microelectronic devices. The system can expose panels of the above size at the rate of 120 per hour.

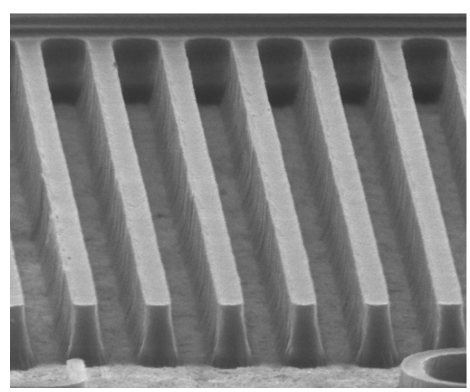

Fig. 6. Results obtained on a large-area projection lithography system for printed circuits. The images show 10 μm lines and spaces in a 13 μm thick liquid resist.

Imaging results obtained in a thick liquid photoresist using the Model 2100 SPE lithography system are presented in Fig. 6. This system is designed for patterning 460 x 610 mm, high-density, multilayer printed circuit boards. It uses a 351 nm XeF excimer laser source and has a 0.025 NA projection lens. Its large depth of focus — 560 μm — minimizes substrate planarity requirements. The exposures in Fig. 6 show 10 μm lines and spaces imaged in AZ-Clariant 9260 resist, coated to a thickness of 13 μm on a conventional FR4 board. This system is also well suited for use with conventional dry-film photoresists. For both liquid and dry-film resists, the exposure speed of this system is < 20 sec per panel. In all of the above imaging demonstrations, the pre- and post-exposure resist processing conditions used were typical and as specified by the resist suppliers. These results demonstrate that the benefits of large-area laser projection imaging are immediately available to the microelectronics industry without requiring any modifications to be made to the current resist materials or processes.

These large-area projection lithography systems, due to their excimer laser source, also function very effectively as photoablation tools. Extensive work has been carried out on direct projection ablation in numerous polymers using such a dual-function system that incorporates a 308 nm XeCl laser. The system is used in the two modes, lithography and photoablation, in essentially the same manner, except that in the latter case, the stage is scanned at a lower speed to deliver a higher exposure dose as required for ablation, and a mask with a higher damage threshold than chrome is employed. A wide variety of polymers, including polyimides, acrylics, polycarbonates, etc., have been thus efficiently ablated in numerous applications in microelectronics and optoelectronics.[8] As an example, in Fig. 7 we show photoablation patterning results obtained in the polymer DuPont Pyralin PI2611D using an Anvik Model 3030 SXE system. This dual-function, large-area projection system incorporates a high-power XeCl laser and has a 0.072 NA projection lens that provides a resolution of 3 μm. In this optoelectronic application, the material was spin-coated on glass plates to a thickness of 5.6 μm and the waveguide trenches were ablated with a dose of ~ 250 mJ/cm^2. We remark that excimer laser photoablation of polymers is widely used in the production of multilayer circuits to form the interconnect vias and in the production of inkjet printheads to form the nozzles.

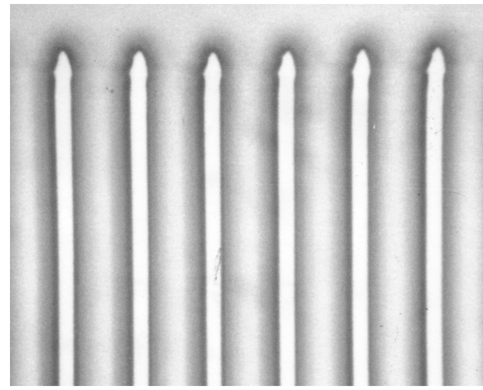

Fig. 7. Projection ablation on a dual-mode, large-area patterning system with a 308 nm laser, showing 8 μm wide, 5.6 μm deep trenches ablated in Pyralin 2611D polymer.

6. CONCLUSION

Large-area lithography is an important requirement in the production of numerous microelectronic, optoelectronic, and microsystem devices. The lithography requirements for the fabrication of such large-format products are distinctly different from those of semiconductor integrated circuits and other electronic devices made using conventional lithography tools. These requirements and distinctions of large-area lithography are discussed. We review a new class of projection lithography systems, developed in recent years, that provide both high-resolution imaging and very large exposure area capability. The systems function as dual-mode, high-throughput production tools, capable of patterning in photoresists as well as photoablation in polymers, making them attractive for high-volume, cost-effective production of numerous large-format products, with feature sizes ranging from 15 μm to below 1 μm and substrate sizes from 150 x 150 mm to 610 x 915 mm. The new lithography system technology, several completed systems, and demonstrated results are reviewed.

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