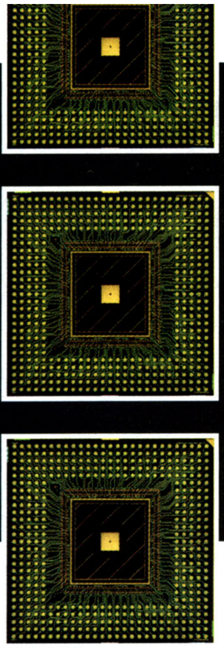

Excimer Laser Projection Imaging for High-Performance Circuit Board Patterning

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A new class of laser projection imaging (LPI) systems has been developed that represents a breakthrough in cost-effective production of high-performance, high-volume PCBs and other microelectronic systems fabricated on large substrates. The new LPI systems provide not only very high resolution and precise alignment but also high throughput with conventional, widely used, dry-film and liquid photoresists, eliminating the shortcomings of contact, laser direct imaging (LDI), and other exposure tools.

Introduction

As advances in electronic systems with higher speeds, greater functionality, and higher densities continue to place greater demands on PCB design and manufacturing, the demands in turn on the PCB production equipment continue to accelerate. Requirements of finer lines, pads, and vias are driving the need for exposure 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 use of conventional photoresists.

Rationale for LPI

There are two primary drivers for the push in development of new imaging systems. The first is the recognition by the global PCB fabrication community of the fact that current tools are at the end of their capabilities. The second and equally important driver is the assessment by industry experts that the limitations of current tools are fundamental; evolutionary advances in the tools that result in marginal improvements will no longer be sufficient to meet the demanding manufacturing requirements.

Contact printers can have low yields due to defects produced in the board and low mask life, and there are also risks of poor alignment performance and off-contact problems due to nonplanarity of board surfaces. Because exposure can be done only after the board and mask are brought in hard contact, whereas the relative positioning between them necessary for precise alignment must be done before the contact, high-precision board-to-mask alignment becomes an issue. Contact printers also use very high-power arc lamps, including inefficient provision of UV radiation, the need for enormous heat filtering, vibrations and thermal distortion, and poor resolution. These limitations are eliminated in LPI.

LDI systems do not require a mask (i.e., artwork), therefore the aforementioned artwork-related issues disappear. In addition, the cost of masks is eliminated, which can be important when a large number of masks are needed, such as would be the case in a manufacturing scenario that requires boards of a large number of different designs but of each design in a small volume. However, because LDI tools pattern the photoresist in a pixel-by-pixel, serial manner (as in a laser printer), they deliver low throughputs and can typically reach minimum feature sizes (MFS) of about 1 to 2 mils. LDI systems also require new, high-sensitivity resists.

LPI systems image the resist by projection printing in a parallel mode (as in a photocopier). They work with conventional dry-film or liquid photoresists, requiring no change in any process step; these systems have demonstrated minimum feature size capability down to 4 μm, or 0.16 mil (and even lower for other applications).

LPI System Technology

LPI systems combine a novel lithography technology with efficient opto-mechanical system engineering. The key features of the system (example shown in Figure 1) are:

Figure 1 LPI Patterning System

- High-resolution projection imaging—minimum feature size (lines/spaces and holes) down to 4 µm (0.16 mil);
- Very precise alignment—layer-to-layer or mask-to-board alignment down to 2.5 µm (0.1 mil);
- High exposure speed—under 20 sec exposure for 460 x 610 mm (18 x 24 in) panels; and
- Large-area substrate handling capability—easily configurable for boards of any size up to 610 x 915 mm (24 x 36 in).

These performance features are achieved with a hexagonal seamless scanning projection technique and a single-planar x-y stage configuration that provide enhanced optical and scanning efficiencies and combine high-resolution, large-area imaging with high-precision alignment capability. There are production systems available that have demonstrated attractive performance using conventional dry-film and liquid photoresists.

The core technology developed for the LPI systems[1-5] is illustrated schematically in Figure 2. The board and the mask (i.e., artwork) are rigidly mounted on a single-planar scanning stage that is capable of moving them in unison in both x and y directions. The illumination system comprises an excimer laser light source and a beam-processing optical system. The excimer laser emits several tens of watts of UV radiation at 351 nm, a wavelength well suited for imaging conventional photoresists designed for mercury arc lamp exposure. 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).

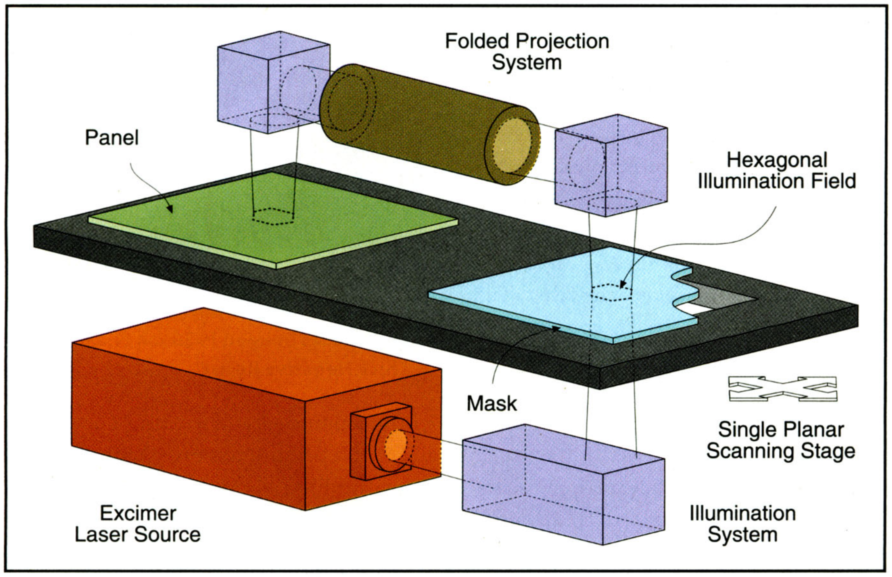

Figure 2 A Schematic of the Laser Projection Imaging Technology, Showing Scanning With a Single-Planar Stage and Hexagonal Beam

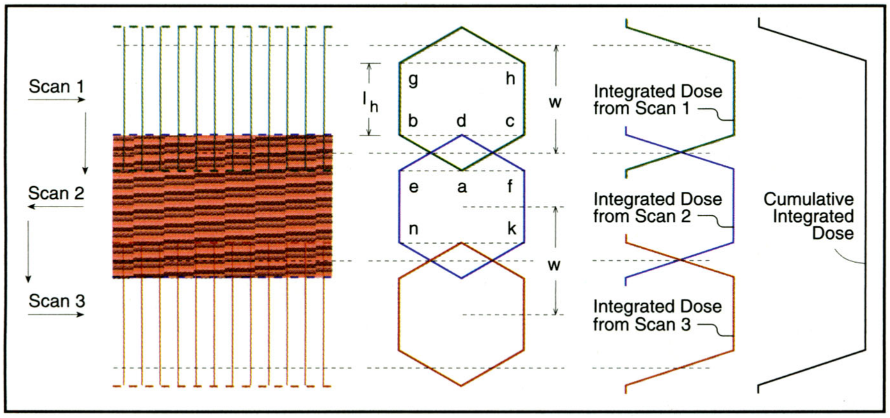

Figure 3 The Seamless Scanning Exposure Mechanism. Adjacent Hexagonal Scans Overlap Partially, Giving Complimentary Dose Profiles. Integrated Doses From Successive Scans Produce Uniform Exposure Over Whole Panel

The mask pattern within the illuminated hexagonal region is imaged onto the board 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 happens: the mask and board 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 to 40 mm; shown as w in Figure 3); the mask and board 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 board is imaged. The hexagonal illumination configuration ensures that the whole exposure is completely seamless and uniform.

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. In each scan, the region swept by the rectangular portion of the hexagon (g-h-c-b or e-f-k-n) does not overlap with its neighboring scans, but the region swept by a triangular portion (a-b-c) is re-swept by a similar triangular portion (d-e-f) in the next scan. Because 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.

Thus, the LPI system, by combining seamless 1:1 projection imaging and high-speed scanning with a single-planar stage, delivers the capability of high-resolution imaging on boards of practically any size with high throughputs. The system is also modular in architecture—its main subsystems are integrated in a mutually non-interfering manner. This important feature permits choice of different user-specified system configurations as well as future upgradability as requirements change with product migration.

LPI System Description

The design and performance specifications of the LPI system for PCB fabrication are shown in Table 1. The light source is a high-power, ultraviolet excimer laser. The systems designed for PCB fabrication use a xenon fluoride (XeF) excimer laser operating at 351 nm, a wavelength ideally compatible with all conventional dry-film and liquid photoresists currently being used with the 365 nm wavelength (i-line) of Hg arc lamps. The XeF excimer laser emits in excess of 45 watts of pure UV radiation, more than an order of magnitude greater than the useful UV radiation from a multi-kilowatt arc lamp used in contact printers or the laser sources employed in LDI systems. This enables the LPI systems to deliver high throughputs not only when imaging with primary photoresists, but also with resists requiring very high exposure doses (e.g., solder-mask resists). The laser operation is fully integrated with the LPI system control software and is run from the main system computer. The other key part of the illumination system is a beam processing unit, which transforms the laser beam to produce a uniform, hexagon-shaped illumination region on the mask.

LPI System Specifications	
Imaging Technique	Seamless scanning projection
Resolution	10 µm (0.4 mil)
Projection System	1:1 magnification refractive lens
Depth of Focus	560 µm (22 mils)
Lens Field Size	50 mm diameter
Panel Exposure Area	460 x 610 mm (18 x 24 inches)
Exposure Source	XeF excimer laser
Exposure Wavelength	351 nm
Alignment Precision	+/- 2.5 µm (0.1 mil)
Alignment System	Automatic
Panel & Mask Handling	Automatic
Exposure Throughput	120 panels / hr (6 sq. ft. / min)

Table 1 Design and Performance Specifications of the LPI System for High-Volume Production of Fine-Line PCBs

The projection lens assembly in the LPI systems is a unit-magnification, refractive imaging system, designed to produce the specified resolution. For the PCB system, the projection assembly provides a minimum printable feature size of 10 µm (0.4 mil) at the exposure wavelength of 351 nm; other systems are available with higher or lower resolution specifications. The field diameter of the lens is 50 mm, which enables simultaneous imaging of over 2.6 million pixels of 1 mil size or 16 million pixels of 10 µm size. In throughput, this illustrates the fundamental advantage 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 board size specifications. The LPI system outlined in Table 1 can handle rigid or flexible substrates up to 460 x 610 mm (18 x 24 in); other systems are available with larger or smaller substrate size specifications. The stage can scan in either direction at speeds up to 500 mm/sec. It holds the mask and the board 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 other imaging 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.

The LPI system is designed to be able to align the mask and board rapidly and automatically to within ±2.5 µm (±0.1 mil). While such alignment precision is highly beneficial for patterning any layer, it is especially attractive for imaging outer layers. The automatic alignment system consists of a set of mask and substrate cameras that view several targets (holes, fiducial marks) on the mask and substrate. The position information for the targets 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 the LPI system is a major advantage over other exposure tools.

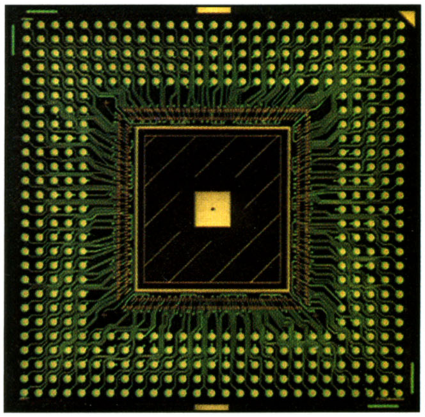

Figure 4 Primary Imaging of a Dry-Film Photoresist, Showing 25 µ (1 mil) traces and 150 µ (6 mil) BGA Pads in a Flip-Chip Flex Module

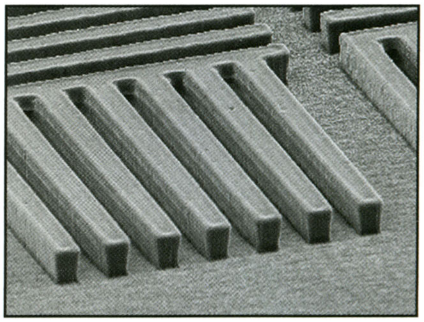

Figure 5 Exposures Made in a Common Dry-Film Resist: 36 µm (1.5 mil) Lines and Spaces Imaged in 30 µm (1.2 mil) Thick Negative Resist

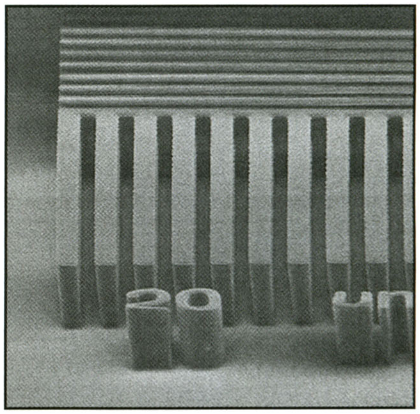

Figure 6 Imaging of Features With High Aspect Ratios, Showing 20 µ (0.8 mil) Lines and Spaces in 70 µ (2.8 mil) Thick Resist

LPI System Performance

The performance of the LPI system has been demonstrated in exposures made in a variety of conventional dry-film and liquid photoresists applied on typical rigid boards and flexible sheets. Figure 4 shows a flexible circuit module substrate for flip-chip attach in which a dry-film resist laminated on a copper-polyimide flexible substrate was patterned by an LPI lithography system. In this primary imaging application, 25 µm (1 mil) traces and 150 µm (6 mil) BGA pads were cleanly patterned. Figure 5 shows results obtained in a common dry-film resist. The 30 µm (1.2 mil) negative resist was laminated on a standard FR-4 board. All processing conditions used, including lamination, exposure dose, and development parameters, were typical for this resist and as specified by the supplier. The figure shows scanning electron micrographs of 36 μm (1.5 mil) lines and spaces. These results demonstrate that the LPI requires no changes in current photoresists or processes.

Figure 6 shows imaging of features with high aspect ratios that are desirable in fabricating structures, such as microelectromechanical systems and microfluidics, including a variety of sensors, valves, and gears. The figure presents 20 μm (0.8 mil) lines and spaces patterned in 70 μm (2.8 mil) thick resist.

Figure 7 presents imaging results obtained in a liquid photoresist. The resist was coated to a thickness of 13 μm (0.5 mil) on an FR-4 board. All processing conditions, as with the dry-film resist, were standard and as specified by the supplier. The figure shows 10 μm (0.4 mil) lines and spaces. It can be seen that the LPI systems are attractive for today's high-volume PCB manufacturing but also meet the high-resolution, high-throughput imaging requirements of future product generations that will use designs incorporating sub-mil features.

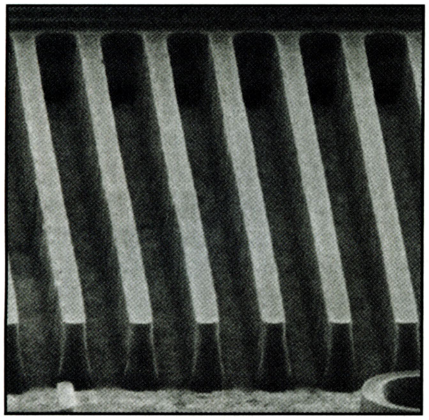

Figure 7 Imaging of 10 μ (0.4 mil) Lines and Spaces in 13 μ (0.5 mil) Thick Liquid Resist

LPI technology also extends to deep-UV imaging with very high-resolution capability. In these machines, the illumination source is a XeCl (308 nm) or KrF (248 nm) excimer laser. Exposure systems using these lasers are also ideally suited for photoablation in various polymeric dielectrics, making such machines attractive for via generation and laser embedded circuit formation.[6] Figure 8 shows high-resolution imaging by a deep-UV lithography and photoablation system, showing feature sizes of 5 and 3 μm, demonstrating the extremely high resolution possible with this technology.

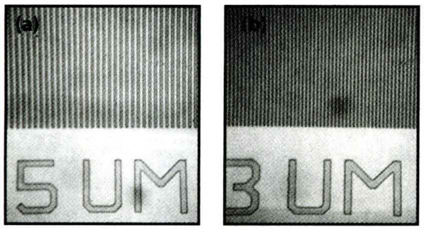

Figure 8 High-Resolution Imaging Showing Lines and Spaces of (a) 5 μ width and (b) 3 μ width

The LPI system provides an exposure time of 19 sec for 18 x 24 in panels with common dry-film or liquid resists. With an overhead time of 10 seconds (for load, unload, and align), the system delivers a net throughput of 125 boards/hour. Note that this throughput is independent of both the sizes and the densities of the patterned features. In high-volume production, tens of thousands of boards can be exposed using the same mask. Because the LPI system operates at conventional exposure doses at a conventional wavelength, it uses conventional masks, which can be Mylar or glass. When the cost of such a mask (USD 25 to 200) is included in a cost-of-ownership calculation for a production run of tens of thousands of boards, the impact of the mask cost can be seen to be negligible. The LPI system, therefore, is optimally suited for high-volume, low-cost manufacturing.

The throughput value of 125 boards/hour is realized with the LPI system for any photoresist with a dose requirement of 120 mJ/cm^2 or less. For resists that require exposure doses below 120 mJ/cm^2, the system attenuates the laser beam to use lower power because the throughput-limiting parameter is the maximum stage scanning speed of 500 mm/sec. For resists requiring doses above 120 mJ/cm^2, the proper exposure is obtained by scanning at speeds below 500 mm/sec; the maximum laser power thus becomes the limiting factor. For example, for exposure doses of 150, 300, and 500 mJ/cm^2, respectively, exposure times will be 23, 47, and 78 seconds and the net throughputs will be 108, 64, and 41 boards/hour.

There are also technologies available that further enhance the LPI systems for high-volume manufacturing of fine-line printed circuits. The first is variable-area substrate tiling, which enables the system user to rapidly and flexibly configure the partitioning of the board to pattern modules of different sizes, while still deriving the major cost benefits of large-format processing. The second enhancement is anamorphic x-y scaling, which provides independent image size adjustment along x and y to compensate for dimensional changes in the panel that may occur during any processing steps. Due to space limitation, we will describe these additional system features in a forthcoming publication.

Conclusion

LPI systems provide not only very high resolution and precise alignment but also high throughput with commonly used dry-film and liquid photoresists. Demonstrated results show that this class of systems eliminates the limitations of contact, LDI, and other exposure tools. LPI systems are attractive as cost-effective solutions for volume production of high-performance printed circuits, displays, flex circuits, and other microelectronic systems fabricated on large substrates. ☐

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