# High speed maskless lithography of printed circuit boards using digital micromirrors

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## ABSTRACT

The printed circuit board (PCB) industry has long used a lithography process based on a polymer mask in contact with a large, resist-coated substrate. There is a limit to this technique since both the masks and PCB substrates themselves may undergo distortion during fabrication, making high resolution or tight registration difficult. The industry has increasingly turned to digital lithography techniques which, in addition to eliminating the masks, can actively compensate for distortions. Many of these techniques rely on a "dot-matrix" style exposure technique that uses "binary" pixels and small pixel or dot spacing to achieve the required resolution. This results in limitations in write speed and throughput, since many small pixels or dots must be written over a relatively large area PCB substrate. A patented gray level technique[1] based on a commercially available digital micro-mirror device (DMD) achieves required resolutions with a relatively large projected pixel size, and thus offers a higher speed alternative to conventional digital techniques. The technique described is not limited to PCB, but may be applied to any lithography or printing-based application where high speed and accurate registration are concerns.

**Keywords:** PCB, printed circuit board, DMD, LDI, laser direct imaging, gray level imaging, digital lithography, maskless lithography

## 1. INTRODUCTION

Printed circuit board (PCB) manufacturing comprises many process steps. Each individual step must be closely monitored and controlled in order to minimize excessive combined tolerance errors, particularly with regards to layer-to-layer and via-to-pad registration. One source of such tolerance errors is the mask (often called a "photo-tool" or "artwork") used in the image transfer to PCB layers. The industry has traditionally relied on a lithography process based on a polyester mask in contact with a large, resist-coated substrate. The feature placement accuracy of these masks is subject to the accuracy of the photoplotter that prints them, the skill of the operator who manually sets them, and the effects of temperature and humidity, which can unevenly distort the polymer material. As interconnect densities continue to increase, the design budget for these errors is reduced to the point where reliance on operator skill and increased investments in environmental controls for mask manufacturing is ineffective. The need for new manufacturing technologies that eliminate operator variation and masks is increasingly needed to manufacture consistent and predictable production yields.

Another important source of error is the distortion of layers during lamination and handling, which can make it difficult to overlay and register subsequent or outer layers. The heat and pressure during lamination of multiple layers often causes dimensional distortions of the base materials used in both rigid and flexible PCB layers. This distortion is dependant on numerous factors including batch-to-batch variations from the supplier, variations in the laminating and handling processes at the fabricator site, and even the specifics of the PCB design itself. Traditionally, the conditions that lead to such distortions and the resulting tolerance stack-ups have been well characterized, such that scaling "rules of thumb" and other design guidelines could be applied to overlaying mask patterns in order to register them properly. However, the trend toward decreasing feature sizes and increasing interconnect densities has driven the need for more advanced registration techniques, particularly the ability to compensate or pre-distort CAM (Computer Aided Manufacture) image data with reference to the actual substrate dimensions. The precise and at times non-linear correction factors applied to CAM data now often dictate product yields on large panels having challenging feature dimensions.

Digital imaging, or maskless lithography, where image data can be optimally scaled or distorted just prior to writing, addresses the specific needs for registration, as well as for the elimination of process steps and masks that contribute greatly to alignment errors. The total installed base of digital imaging tools at the end of 2010 is reported to be approximately 820+ units which represents a dramatic year-on-year growth rate close to 40%.[2] Most of these are laser direct imaging (LDI) tools, in which a pulsed laser beam is raster scanned across the panel substrate to form a pixelated image. However, the burgeoning market for digital tools has drawn many new manufacturers to the space over the past several years, each with their own unique print methodologies, applications and value set. Although they provide the enhanced digital capabilities required for tight registrations and smaller features, most technologies, including LDI, are slow compared to the traditional contact printer. Hence, the contact printer is still used for all but the most difficult layers or jobs. Therefore, the general adoption of digital imaging as a replacement for mask-dependant contact printing will largely depend on the conjunction of all the following factors:

- Acquisition and running costs
- Print speeds and panel throughput
- Registration accuracy
- The ability to quickly rescale data using both linear and non-linear algorithms

This paper describes a unique method of digital printing that satisfies the above requirements. It is based on Texas Instruments DLP® (Digital Light Processor) technology, and it employs a digital micromirror device (DMD) and optical system similar to those inside commercial DLP® projectors and HDTVs. A multiplicity of identical optical systems is arranged to address a scanning substrate in parallel, and a patented gray level technique[1] is used to achieve resolution that is a small fraction of the projected mirror pixel size. The result is a maskless, digital lithography machine that delivers extraordinarily high print speeds and accurate registrations for the large area panels (18x24") and feature sizes (≥50um) common in PCB manufacture. The same techniques and concepts can be scaled to larger or smaller areas, or feature sizes, with the same advantages in speed over other digital lithographic technologies such as LDI or dot matrix printing. **Figure 1** depicts MLI's 7 channel 2027 unit, of which two units have been running reliably in a customer's PCB factory for over a year.


**Figure 1** The Maskless Lithography, Inc. Model 2027 digital lithography machine.

# 2. SYSTEM OVERVIEW

## 2.1 DMD

In order satisfy the speed and throughput requirements for exposure for an area as large as a PCB, multiple identical projection channels are employed, with each operating simultaneously in parallel to expose a portion of the overall area. Each channel consists of a UV light source, illumination optics, a digital micromirror device (DMD), and a projection lens. At the heart of each channel is a Texas Instruments 0.7” XGA DMD. It is an array of 1024 x 768 micromirrors on a 13.68um square pitch, where each pixel element is a square mirror designed to rotate between two states in response to electrical signals. In one state, sometimes called the ON state, the mirror is rotated, or “flipped”, in such a way that incident light is reflected from the mirror and directed through the projection lens to a substrate, forming an image of the mirror. In the opposite state, or OFF state, incident light is reflected away from the projection lens and does not reach the substrate. **(Figure 2)** Although in principle other spatial light modulators could be used, such as LCDs or grating light valves, the combination of fast switching speeds (~44-130 us/frame), UV capability, and wide commercial availability made the DMD a convenient choice for this application.

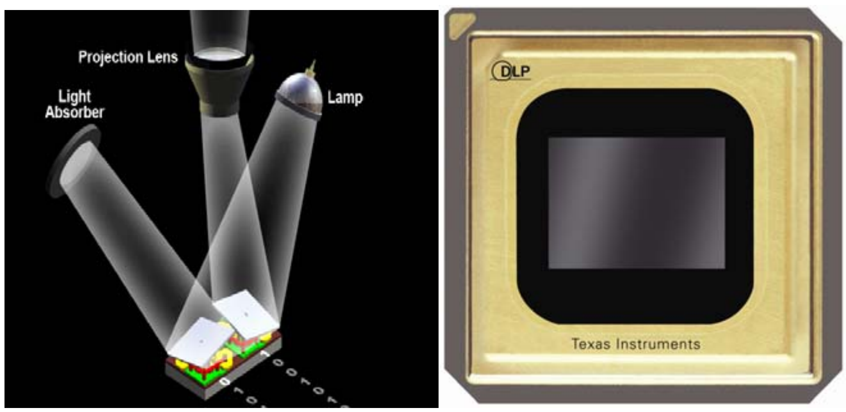
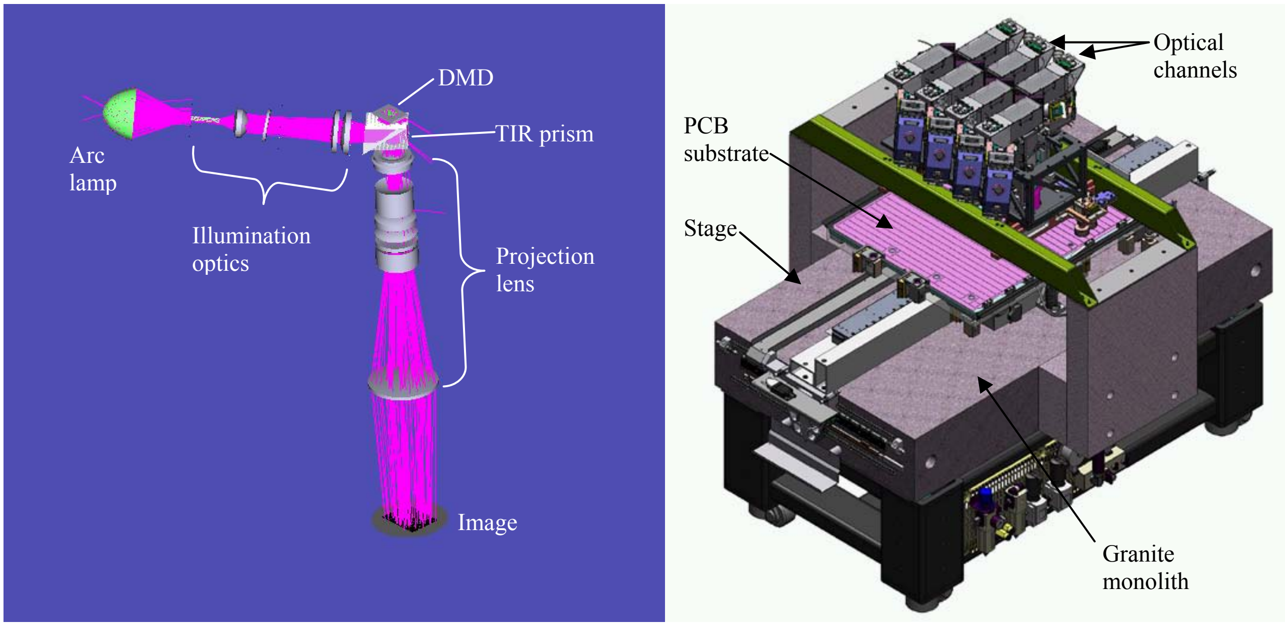



**Figure 2** Left drawing shows the principle of operation for individual micro-mirrors in Texas Instruments’ DMD. The mirrors are spaced on a 13.68um pitch, and flip about an axis at 45$^{o}$ azimuth. The mirrors can be in one of two rotation states, either +11$^{o}$ or -11$^{o}$ about the axis. Either state may correspond to the ON or OFF state depending upon the direction of illumination. In the drawing the mirror on the right is ON, such that light is directed to a projection lens, while the left one is OFF, directing light away from the lens to an absorber. At right is an image of the DMD package. The central rectangular area is the micromirror array.[3]

## 2.2 Optics

Each DMD is illuminated with UV light from a 200W mercury metal halide arc lamp, filtered to pass only the spectral region encompassing the mercury I (365nm) and H (405nm) lines. **(Figure 3a)** The light is conditioned to uniformly illuminate the DMD via an illumination scheme similar to that found in many commercial DLP® projectors. It consists of an integrating rod, collection and relay optics, filters, and a TIR (total internal reflection) prism, which folds the incoming illumination onto the array at the requisite illumination angle, while simultaneously allowing the outgoing projected light to pass with minimal attenuation. Each channel's 2.5x magnification, bi-telecentric projection lens images its respective array onto a resist-coated substrate, forming multiple separate image areas on the substrate, each 35x26.25mm. The size of each projected mirror pixel on the substrate is 34.2um. The number of optical channels can be varied to suit the print speed and cost requirements of the customer.




**(a)** **(b)**

**Figure 3** **(a)** Optical layout for a single channel. **(b)** Channels as integrated into a 7-channel machine. Channels are shown mounted above the precision stage that moves the substrate.

### 2.3 Stage and Scanning

The substrate is driven beneath the optics by a high accuracy air bearing stage. **Figure 3b** depicts the stage and the integrated optical channels mounted above it. The stage system is comprised of an X-Y stage with Z-tip-tilt-theta capability, a vacuum chuck, and isolation damping. The planar air bearing X-Y axes with linear motors are supported on a granite monolith which provides a flat and stable reference. The optics are secured to this structure as well. The modulation of the DMD mirrors is coordinated with the stage position through Zerodur® (zero thermal expansion glass-ceramic) linear encoder scales. The result is a stage with an overall X-Y accuracy of +/-3um.

The channel images are staggered in the horizontal direction by the width of one projected channel image as shown in **Figure 4.** The stage moves in a serpentine pattern to expose strips of resist in an interlaced fashion. When an operator loads a panel, the system uses special cameras and algorithms to quickly position and orient the stage so that the subsequent scanned image will be correctly aligned on the substrate. The stage then proceeds to scan the panel forward continuously in the vertical direction across the staggered images, forming multiple exposed “strips” on the resist. At the end of each scan the stage jogs horizontally by the width of one channel image, and returns in the opposite direction to expose the unexposed areas. The number of passes required to cover the full panel area depends on the number of optical channels. **Figure 4** shows a 7 channel system, which takes two passes to cover the 18x24” panel shown.

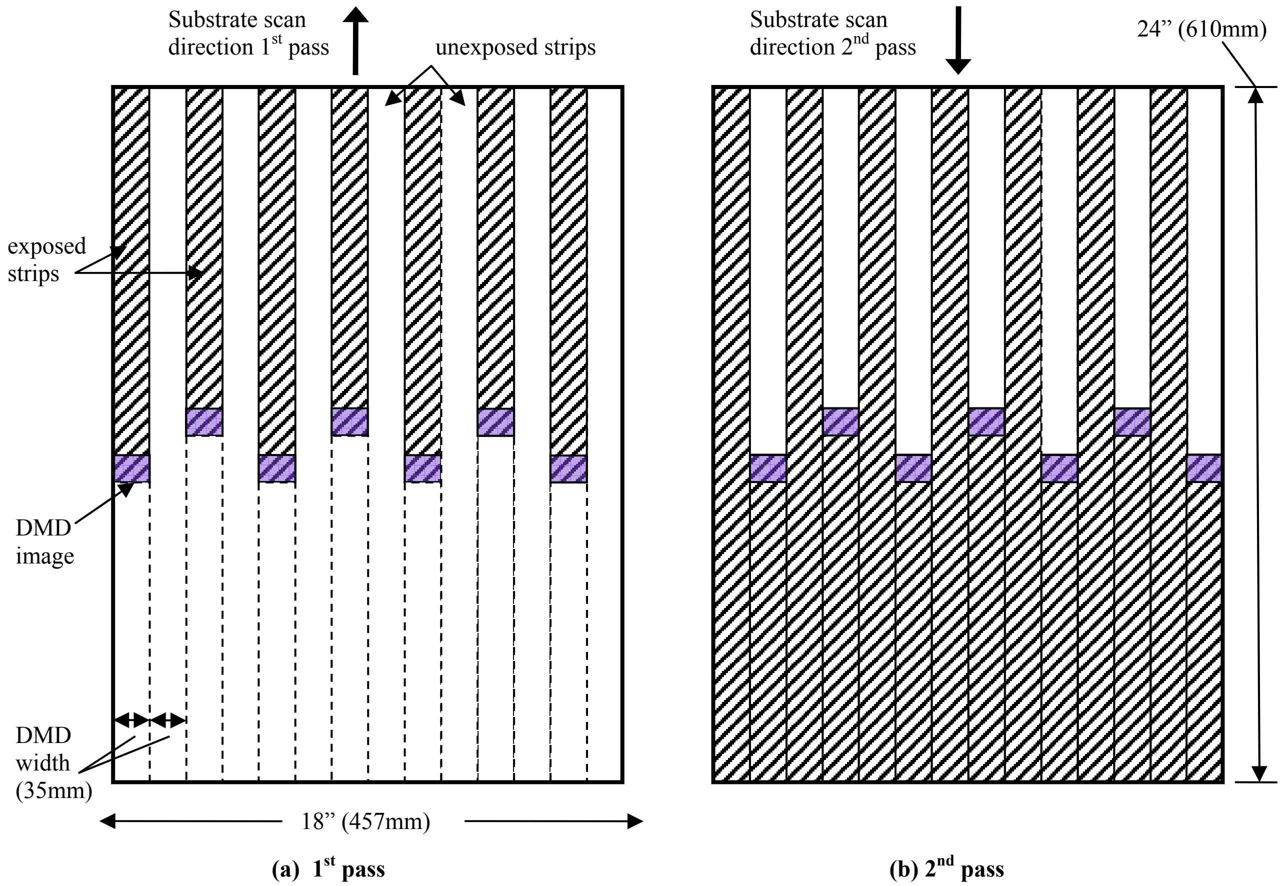



**Figure 4** Scanned exposure of a typical PCB panel for a 7 channel system. Projected DMD images are staggered by the width of one image. Two interlaced passes are needed to cover the area. (a) First pass (b) Second pass

## 2.4 Gray Level Dosing Scheme

Each of the multiple DMD images is carefully aligned and oriented so that its mirror columns are parallel to the stage motion during the exposing scans. This means that, at some time during the scan, each point on the substrate passes under an imaged column of 768 DMD mirrors. As it passes it receives doses, in serial, from some fraction of the 768 mirrors in the column. Whether or not a pixel receives dose from an individual mirror depends on whether that mirror is "ON" ("flipped" to direct light through projection lens) as the point passes under its projected image. Thus, in theory any point on the substrate can receive partial energy in discrete gray level increments up to a maximum of 768, or the total number of mirrors in a DMD column. It is this gray level control of exposed image "pixels" that allows for fine placement of feature edges using relatively large projected mirror "pixels" (34um). This is discussed in more detail in Section 3. **Figure 5** illustrates the dosing scheme for a hypothetical DMD with 5x4 mirrors. As regions A, B, and C are moved across the image, region "A" acquires the maximum possible dose, while "B" and "C" acquire partial gray level dose. The gray level of each "pixel" to be exposed is stored in computer memory as an 8 bit binary number, which effectively instructs the controlling computer what fraction and exactly which mirrors of the 768 to switch "ON" as the substrate "pixel" traverses its respective DMD image. **Table 1** shows the gray level data (stored as 3 bit number) and DMD mirror instructions for the hypothetical dosing scheme depicted in **Figure 5**.

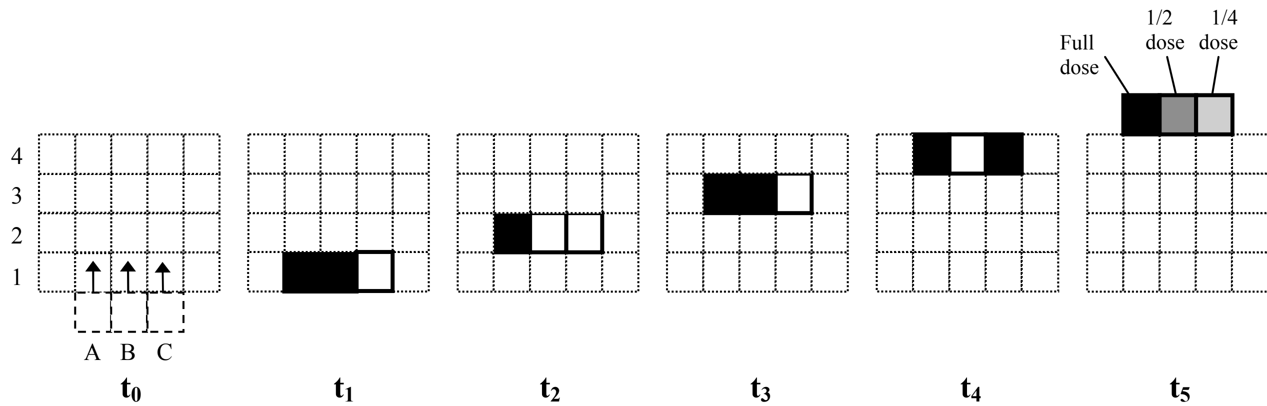



**Figure 5 Gray level dosing scheme**. This simplified drawing shows how individual substrate regions A, B, and C each acquire a different dose as they are scanned under DMD images. For the purpose of this illustration the DMD is a 5x4 mirror array, shown at times $t_0$, $t_1$, $t_2$, $t_3$, $t_4$, and $t_5$. In each increment the substrate advances a distance of exactly one mirror image and the DMD image updates one frame. At time $t_0$ the unexposed substrate regions A, B, and C are about to be scanned under the DMD mirror images. The pictures for times $t_1$ to $t_4$ follow the progression of A, B, and C as they are moved across the DMD image and show which mirrors are activated as they pass. Black represents an "ON" mirror and white is "OFF". Upon completion of the scan, region "A" has received dose from all 4 mirrors in a column, "B" has received dose from 2 mirrors, and "C" has received dose from only one mirror. The picture at $t_5$ shows resultant doses. Region "A" has received the maximum dose, represented by black, and regions "B" and "C" have received partial doses represented by shades of gray.

**Table 1 Data for gray level dosing scheme of Figure 5.** Table shows binary number stored in gray level bitmap image for the exposed regions A, B, and C of **Figure 5**, the corresponding instructions to specific DMD mirrors in time, and the resulting dose for each region. The actual dosing scheme is analogous, except that there are 256 possible gray levels, stored as an 8 bit binary number, and there are 768 mirrors in a DMD column, meaning 768 frames are required to expose each region (as opposed to 4 shown here and in **Figure 5**).

| **Substrate Region or "Pixel"** | **Binary Number Stored in Memory** | **Instructions Expanded to DMD Mirrors** | | | | **Resulting Dose** |
|---|---|---|---|---|---|---|
| | | $t_1$ / Row1 | $t_2$ / Row2 | $t_3$ / Row3 | $t_4$ / Row4 | |
| A | 100 | ON | ON | ON | ON | 4 |
| B | 010 | ON | OFF | ON | OFF | 2 |
| C | 001 | OFF | OFF | OFF | ON | 1 |

While in theory 768 gray levels are possible (one per DMD row), since an 8 bit binary number is used to store the gray level information, there are actually only 256 levels available in the current scheme (meaning more than one column mirror switches "ON" per gray level). Furthermore, some of the gray levels are used to effectively smooth out non-uniformities in the illumination across the DMD and between DMDs. For example, a column that happens to fall in a relatively bright region of illumination will deliver a higher total dose than a column in a dimmer region when all of its respective mirrors, or gray levels, are used. Therefore, the column from the brighter region would use fewer than the full 256 gray levels in proportion to the amount of intensity that needs to be scaled back to equal the intensity of the "dimmest" column. This means fewer than the 256 gray levels are available for gray level dose increments in this particular column. However, the number of gray levels remaining (typically 128 or more) is more than adequate to provide fine resolution of feature edges, as shown in Sec. 3.2.

### 2.5 Dose Relationships

The total dose energy ($mJ/cm^2$) received by a point, or pixel, on the substrate is not only dictated by the number of active, or "ON", projected DMD mirror images that it traverses on a scan, but also the irradiance ($mW/cm^2$) of each projected DMD mirror image, and the dwell time under a projected mirror image as the point passes across it. The dwell time, in turn, depends on the scan speed. The following equations illustrate these relationships.

Assuming that the illumination across a DMD's field of view is uniform, that is, every projected mirror has the same irradiance, $I_m$ [$mW/cm^2$], then the total dose [$mJ/cm^2$] received by a point on the substrate is given by

$$D = I_m T N \tag{1}$$

where $I_m$[$mW/cm^2$] is the irradiance at the substrate for an activated mirror, $T$ [sec] is the dwell time under one mirror image as it passes, and $N$ (0 to 768) is the total number of active or "ON" mirrors seen by the point as it traverses a projected mirror column. The stage velocity and the DMD frame rate are synchronized such that a point on the substrate moves exactly the distance of one projected mirror image (in this case 34.2um) during the time of a single DMD frame. This time is given by

$$T = \frac{P}{v} \tag{2}$$

where $P$ is the projected mirror size at the substrate (34.2um) and $v$ is the stage velocity. Combining (1) and (2), the dose is given by

$$D = \frac{I_m P N}{v} \tag{3}$$

Therefore, for a given irradiance and projected mirror size, the dose can be controlled by the scan speed or the number of mirrors activated on a scan. In principle a very large dose can be achieved if the stage moves slow enough. The goal of course is to project an irradiance high enough that stage can move as fast as possible for high throughput. However, there is a lower limit on $T$, the time spent beneath a projected mirror, and therefore an upper limit on the stage velocity v. In order to ensure that a point receives dose from only 1 mirror per DMD clock cycle (the time for a single frame) , $T$ must be no less than the minimum frame period of the DMD ($T >= 1/F_{max}$), where $F_{max}$ is the maximum frame rate of the DMD. This frame rate sets the upper limit on the stage velocity through Equation 2., and is typically between 7,000 and 22,000 frames/sec, depending on the particular DMD.

Equation 3 is simplistic in that it assumes $I_m$ is constant. In practice $I_m$ will vary somewhat across the DMD image, and thus for a point on the substrate scanning across it, $I_m$ will be a function of time, specifically $I_m(x+vt)$, where $x$ is in the scan direction, $v$ is scan velocity, and $t$ is time. $N$ also becomes a binary function in time $N(t)$. It can be either 0 or 1 in time, and represents the times during which a substrate point receives light from an active DMD mirror. The total dose $D$ for a substrate point is then an integral over the time spent under the DMD image. It can also be readily seen how, for non-uniform illumination, where $I_m$ is different across the projected DMD images, $N$ must be varied for different mirror columns in order to achieve an equivalent dose for points scanned across those columns. As explained above in Sec 2.4, this is exactly how the system compensates for non-uniform illumination across the DMD images.

### 2.6 Computer Architecture and Data Flow

Whether or not a particular DMD mirror is switched to reflect light into the projection lens as a particular point on the substrate passes under its image is controlled by computer. However, a few operations happen beforehand to convert raw image data into instructions for the DMD mirrors. **Figure 6** shows the data flow for this process. The raw data for the printed pattern is stored in the Gerber file format, a vector file format that is standard in the PCB industry. It originated as the vector specifications used to drive the photoplotters that make the masks for mask-based contact printers. A typical job begins with 2 Gerber files (one for each side of a panel) downloaded to a main computer along with a XML file containing operator print instructions, and a file containing custom scaling and distortion parameters for the layers to be printed. The distortion parameters may either come appended to the Gerber data if they are known beforehand, or they may be automatically calculated via special alignment cameras and algorithms that locate key fiducials or targets on the layer to be overlaid.

The main computer sends the Gerber data along with distortion parameters to multiple host computers, each of which controls a particular DMD channel. Each host computer then converts the raw vector file into the scaled, distorted, and cropped "strips" of gray level images to be printed by its respective DMD. These gray level image "strips" are then sent to a memory board controlled and accessed by a local FPGA, where they are ready for real time expansion and upload to the DMD at time of print. During printing, the local firmware expands the gray level data into individual binary image frames that are sent sequentially to the DMD. This expansion is extremely fast and happens in real time as the panel is scanning across the DMD image. Whether a particular mirror of a frame is switched "ON" or "OFF" is determined by the binary number associated with the image point, or "pixel," passing the mirror's projected image at the time of the frame. As with **Table 1** above, a binary number with only the most significant bit filled might mean that every other DMD mirror gets activated as that image point is transferred down the column. This would result in 384 out of 768 mirrors activated, for a gray level of 50% of maximum.

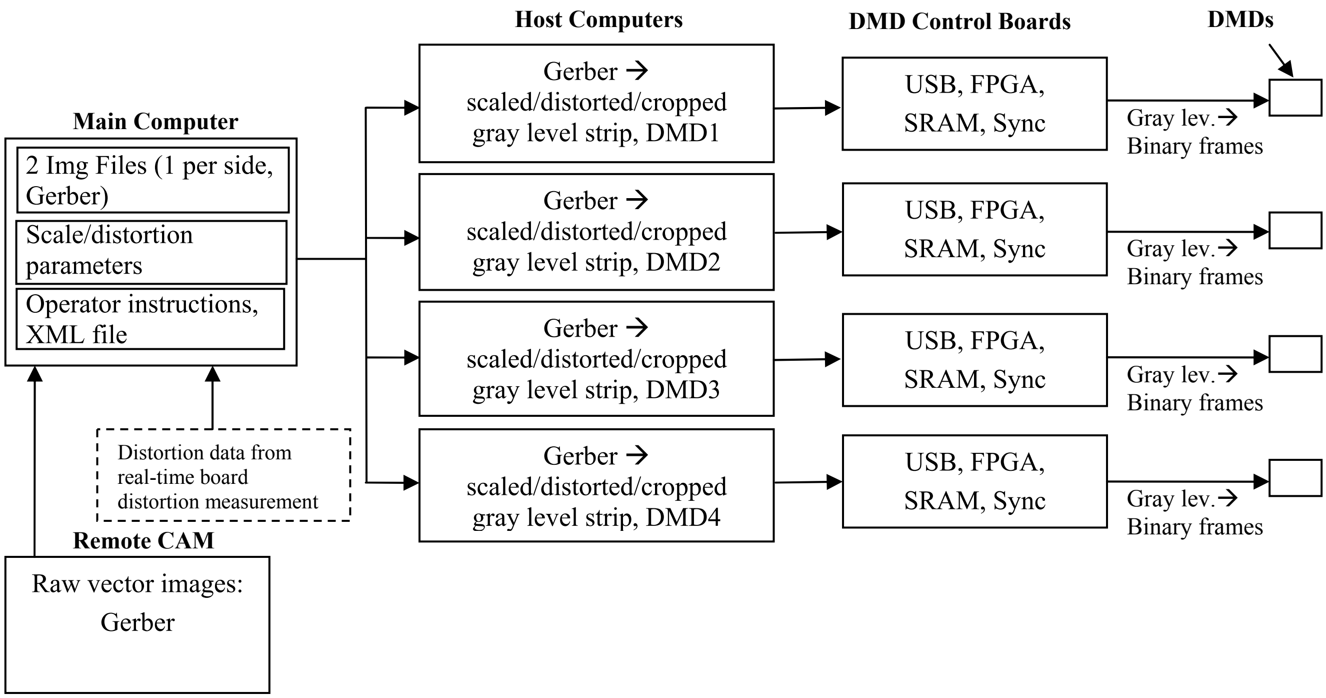



**Figure 6 Data flow.** Flowchart shows flow of image data from origin to DMDs. Vector image data is sent from remote CAM to main computer, which passes it along to DMD host computers along with measured or known distortion parameters. The host computers convert the vector data into scaled, distorted, and cropped gray level image strips to be printed by their respective DMDs. The gray level bitmap is sent to memory on a DMD control board, and during print is expanded (via FPGA) in real time to a sequence of binary frames sent to the DMD. The DMD frames are synchronized with the stage position. Note that this figure depicts 4 channels, though in practice there can be any number.

## 3. GRAY LEVEL IMAGING

### 3.1 Gray Level Imaging Described

In this application, it is gray level imaging (GLI) that provides both high speed and fine feature placement. GLI has been known and used for some time by various segments of the lithography and printing industries. Some advanced photomask pattern generators use it to produce very finely controlled linewidths to within nanometers while still maintaining reasonable write times.[4]

In essence, GLI exploits the typically vexing and problematic phenomenon in lithography that linewidth or critical dimension can vary with exposure dose. Consider **Figure 7**, which shows the effects of different dose profiles in an ideal

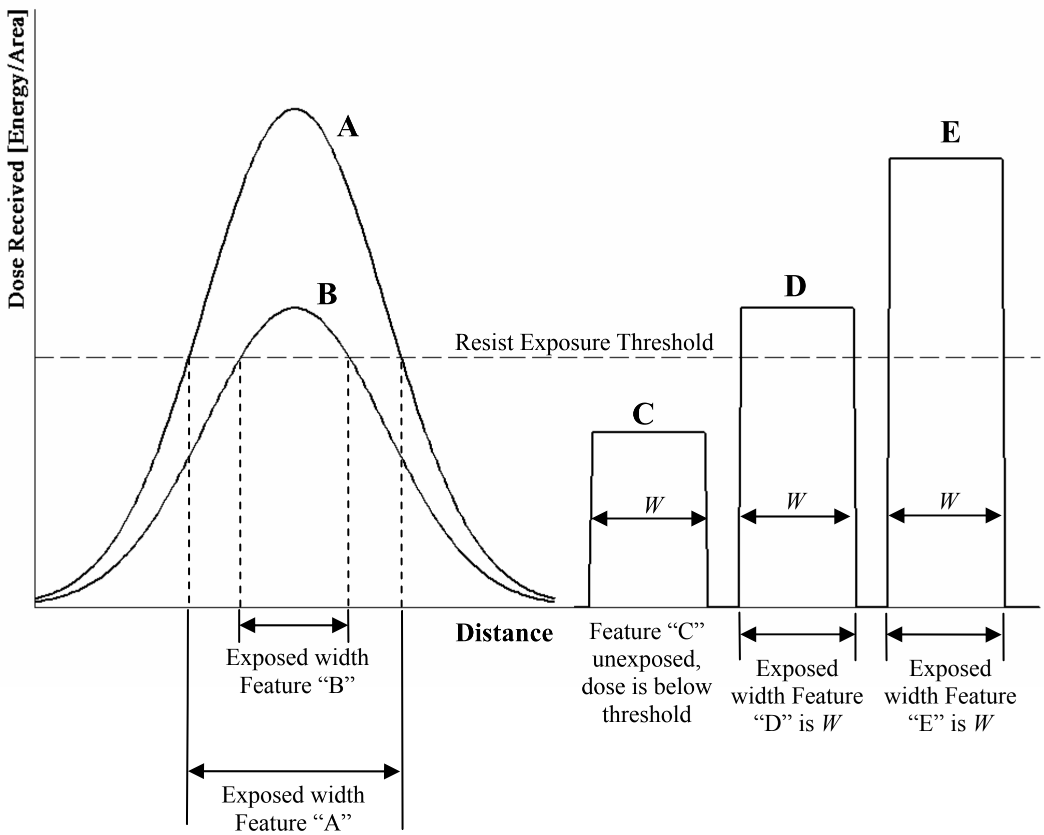



**Figure 7 Gray Level Imaging.** Dose profiles "A" and "B" are examples of Gaussian profiles that might be produced by a "blurred" intensity distribution incident on a photoresist. For these profiles the exposed feature width changes with dose once the resist threshold is crossed. For sharply resolved or "tophat" profiles "C", "D", and "E", the exposed feature width does not change with dose. Hence, a somewhat blurred dose profile is crucial to gray level width control.

photoresist. In the figure, it is assumed that any dose above the resist threshold shown will fully expose the resist, such that upon development it will either be left behind to form a line (negative resist) or be dissolved away to form a space or void (positive resist). The width of the line (negative resist) or space (positive resist) left behind is simply the width of the portion of dose profile lying above the threshold. Profiles "A" and "B" are the same Gaussian profile but at different amplitudes or dose levels. They represent dose profiles that might be transmitted to the resist by a corresponding Guassian, or "blurred", intensity distribution incident upon it. Similarly, profiles "C", "D", and "E" are the same "tophat" profile at different dose levels. They represent dose profiles that might be transmitted by a corresponding ideal "tophat", or sharply resolved, intensity distribution. It is easy to see from profiles "A" and "B" that, once the resist exposure threshold is crossed, the width of the exposed feature is proportional to the total dose applied. The term "gray level imaging" comes from the fact that instead of receiving a binary dose, either fully saturated (white) or completely absent (black), individual image pixels receive an intermediate level of energy, or gray level, in order to tune the widths of features just so.

It should also be apparent from the figure that the *sensitivity* of linewidth to dose depends on the steepness of the slope of the dose profile, or the sharpness of the image that transmitted it. The steeper the slope (sharper the image) the less sensitive the linewidth to dose. To illustrate this, the extreme case of "tophat" profiles "C", "D", and "E", having infinitely steep slopes, is shown for comparison. As the dose of such a distribution is increased there will be a point at which it crosses the resist threshold, exposing a feature that is simply the width of the distribution itself (profile "D"). However, as the dose is further increased, the width of the dose profile lying above the resist threshold does not grow, and so the exposed feature does not grow either (profile "E"). In this case, the feature size is completely insensitive to dose. In practice, although a perfect top hat intensity distribution, or an infinitely sharp image, is unrealistic for a projected image due to the effects of far field diffraction, the example illustrates the fact that if the resolution of the optical system is too high, there may be insufficient sensitivity of linewidth to dose to effect much control over it.

Therefore, a "blurred" image is crucial to the gray level technique. There must be sufficient "blur" of the image to allow for control of the linewidth using dose, but not so much blur that minimum desired features can not be resolved. The trick is to control the blur and strike the right balance between the two. There are various methods to implement such controlled blurring of the image, including defocus, NA reduction, controlled lens aberrations, the use of phase plates in the lens aperture, anti-aliasing filters near the DMD, and the harnessing of motion blur in the scan direction. The photoresist may also have inherent blur that must be accounted for, due to swelling upon exposure, thickness, light scattering, diffusion of inhibitors, processing factors, and the fact that it is never "ideal", with a binary exposure threshold as shown in **Figure 7**.

### 3.2 Gray Level Implementation

**Figure 8** is a mathematical simulation that shows one example of how gray level is employed to control feature edge placement**.** The upper half shows the ideal dose profiles of 4 "Gaussian-blurred" mirror images on a 30um pitch. This pitch is close to the actual projected mirror pitch of 34.2um, and is rounded down to 30um for the convenience of illustration. In this simple case, dose of the leftmost projected mirror is used to control the placement of the left edge of the feature. However, in practice there may be one or more mirrors on the left or right edges of a feature whose dose is optimized to tune the width of the exposed feature. There are infinite combinations of mirror and dose profiles to produce a given feature width, and which is used depends on where the feature falls on the grid of projected mirrors. The leftmost profile is shown for 4 different dose levels ranging from 100% (full dose, same as adjacent pixels) to 25 % of maximum dose. The lower half of the figure shows the resultant dose profiles for each case of left mirror dose level. The resultant dose profile is the linear superposition of the 4 mirror dose profiles, and so the left edge of the resultant profile moves in proportion to the dose level or intensity of the leftmost mirror image. If the overall dose is calibrated such that the resist exposure threshold is about half of the maximum dose, then the edge placement of the developed feature can be controlled easily with a prescribed relationship between left edge position and left mirror dose. It should also be noted that, as discussed above with reference to **Figure 7**, the amount of blur is crucial to attaining the optimal sensitivity of edge placement to dose. Too little blur and there is insufficient sensitivity; too much blur and minimum features may not resolve. The amount of, or degree of blur is sometimes characterized by the full width half maximum (FWHM) of an intensity distribution. For this simulation the FWHM of the Gaussian profiles is set to 40um. Although technically the irradiance profile of an imaged mirror is not Gaussian (It is the convolution of the aberrated optical point spread function (PSF) with the "tophat" mirror profile), the Gaussian function in most cases is sufficient to model the behavior and interaction of the blurred mirror images in practice.

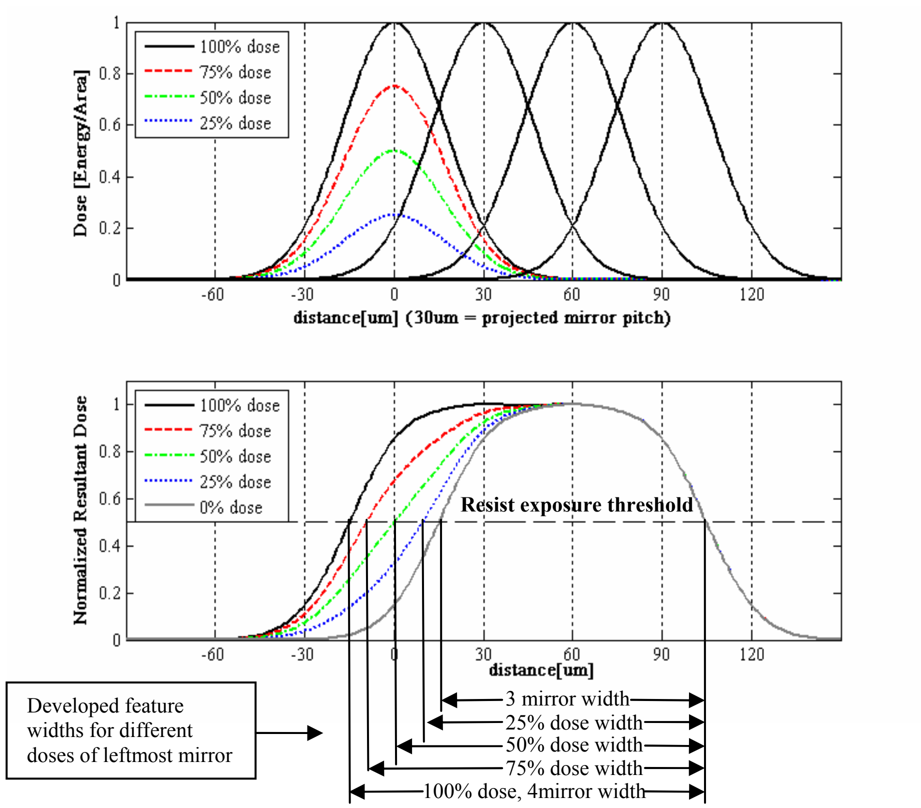



**Figure 8 Simulation of gray level edge control.** Upper graph shows dose profiles for 4 blurred mirror images on 30um pitch. The leftmost dose profile is shown for 4 different dose levels. The lower graph shows the corresponding effect on left edge placement and developed feature width versus left mirror dose.

**Figure 8** essentially illustrates the key concept underlying gray level imaging: that the feature edge can be located to within a small fraction of the projected pixel size itself, depending on the number of available gray levels. The lower graph shows edge placement for 5 dose levels from 0 to 100% on the "edge pixel." Then, with typically 128 dose or gray levels left after correction for illumination (Sec. 2.4), the edge could be located to 1/128$^{th}$ of the pixel size. With MLI's projected mirror pixel size of 34.2um, this would be 34.2/128, or .27um. For 128 gray levels, this is the theoretical limiting resolution of the system, or the minimum increment by which a feature or edge can be moved. Note that this is not the absolute positioning accuracy, sometimes called "addressable resolution", across a full panel. That number depends on a combination of the absolute stage positioning accuracy, stage to camera calibration, and other positional calibration errors. It is about 12um (3 sigma).

### 3.3 Gray Level Imaging in Digital Lithography – Increased Write Speed

One of the primary advantages of digital, or maskless, lithography is that the raw pattern data may be custom scaled, distorted, or otherwise dimensionally altered only moments before the pattern is projected to the substrate. This enables the system to compensate "on the fly" for distortions and scale errors in a layer that the current pattern may intend to overlay. For instance, layers of a PCB may undergo distortion as they are laminated together, meaning that features such as vias, pads, lines, etc. are no longer placed in their nominal location. A digital printing machine is able to measure such distortions with a camera via key fiducials on the underlying layers just before an exposure is made. Then, in order to register the next exposed layer properly, image adjustments can be made quickly to the data before it is printed. With a contact printer or mask based system, an entire new mask would have to be fabricated to register the new layer with the underlying distorted layers, taking 12-24 hours of production time. And even then the mask could only be fabricated to compensate for a measured average of distortions experienced by a particular group of layers, since it would be hopelessly impractical to make a new mask for each individually distorted board in production. A digital machine, however, can in theory compensate exactly for the distortions of each individual PCB layer that passes through it, thus enabling much smaller features sizes and drastically tighter registrations. Therein lies the profound advantage offered by a digital, or maskless, lithography tool.

For most existing digital writers, however, this empowering capability comes at the great expense of speed. Fundamentally, this is because most digital printers rely on printing enough individual dots, or pixels, to achieve the feature size and positioning resolution required, similar to a dot matrix printer. While this may be fine for a very small area, it is extremely inefficient for an area as large as a typical PCB panel (18"x24" or larger). For such a large area it is very hard to compete with a mask-based contact printer, which exposes the entire area of both sides of a panel at once. For this reason, PCB fabs presently continue to use the mask-based contact printers for typical high volume jobs, and only resort to digital machines for jobs or layers that have extremely small features or tight registration requirements. Gray level imaging, however, uses larger projected pixels to achieve the same or better grid resolution, and thus covers a larger area for a given pixel modulation rate, resulting in higher throughput.

Sec. 3.2 shows how gray level imaging can locate features to within a small fraction of the pixel size itself. This is in contrast to dot matrix or binary pixel techniques, where the dot or pixel size must be on the order of the desired feature positioning resolution. The resulting larger pixel size of the gray level technique delivers two key benefits: (1) fewer pixels to print per unit area (2) slower data rates required to cover equal areas in equal times. To understand why, consider two identical DMDs with 13.7um mirror pitch, one of which employs gray level pixels and the other binary pixels to achieve the same required resolution and minimum feature size. A typical PCB design rule of today might require minimum feature (line/space) sizes of 50um aligned to a 5um grid, meaning that feature edges must be located to within +/-2.5um. To accomplish this with binary pixels requires a projected pixel size on the order of 5um, or a 0.36x optical magnification in our example. As described above, a gray level technique with 256 gray levels can achieve practically unlimited, or "gridless", resolution with a much larger pixel size. For the gray level system, the design choice is then to decide how large the projected pixel can be and still print the 50um minimum features. It turns out that the minimum feature size that can be printed with sufficient gray level edge control is about 1.5 times the projected pixel size, and this is the basis for MLI's system choice of a roughly of 34um projected mirror size, or 2.5x optical magnification. Thus, the projected gray level pixel size is about 7 times that of the binary pixel, and covers 49 times the area! (**Figure 9)** In order to print the same area in the same amount of time, the binary pixel technique either needs a 49x faster scan speed and data rate, or more DMDs in parallel. The former may seem possible at first glance, since the irradiance (mW/cm$^2$) for a given illumination scales as the inverse of the pixel area (or magnification squared). This means the irradiance of the binary pixels is 49x greater than the gray level pixels in our example, so they would need only 1/49 the exposure time to deliver an equivalent dose in mJ/cm$^2$. However, aside from the mechanical challenges involved with greater stage speed and acceleration, recall from Sec 2.5 that there is a minimum dwell time under a projected DMD mirror. This dwell time is 1/(maximum frame rate), or about 44us for the most recent DMD models. If the gray level technique already prints at the maximum frame rate (as is the case with MLI's system), there is no room to switch the DMD mirrors and move the stage faster to take advantage of the increased irradiance. *The data rate is fundamentally limited by the frame rate of the DMD, and so any technique that requires more pixels to be imaged at the maximum frame rate will be inherently slower.* Adding more DMDs can offset the problem, but at the expense of greater cost and complexity.

Laser direct imaging (LDI), the most common digital lithography technique used in the PCB industry today, and in which a modulated laser beam is raster scanned across the substrate, suffers from similar limitations in data rate due to the digital modulation bandwidth of the acousto-optic modulators used to modulate the beam, and/or the available laser power.[5] The limited CW or "quasi-CW"[5] laser power currently available at 355nm requires LDI to employ special high sensitivity resists in order to obtain the high throughputs required.

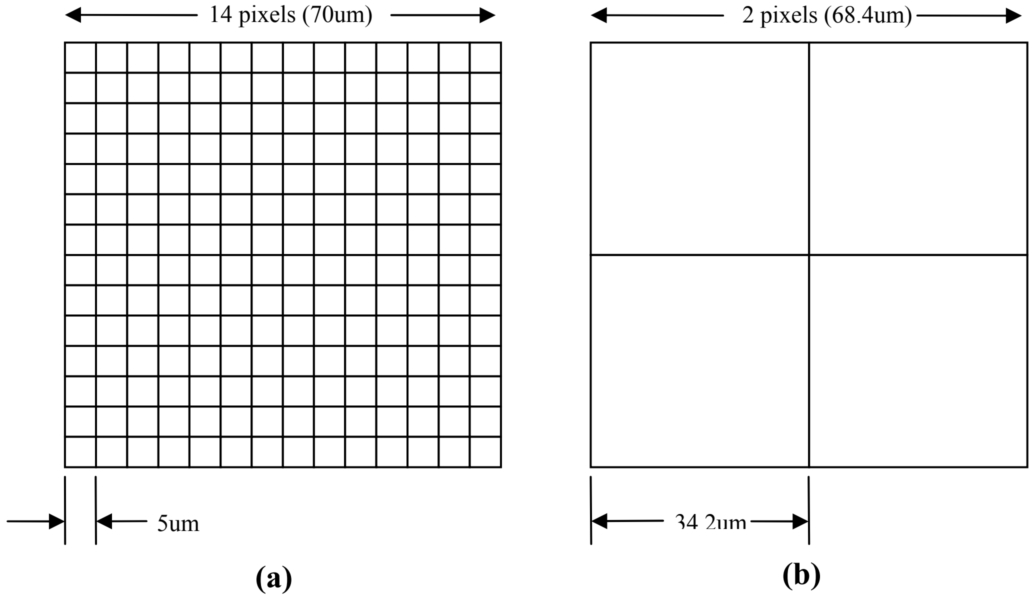



**Figure 9** Comparison of pixel sizes in a binary "dot matrix" style scheme and gray level scheme that both provide similar feature placement resolution. (a) Binary pixels for feature placement of +/-2.5um. (b) MLI gray level pixels for feature placement of better than +/-2.5um. There are ~49 binary pixels for every gray level pixel.

## 4. RESULTS

MLI currently has two production machines of their 7-channel Model 2027 (**Figure 1**) running at a customer's PCB factory. Both have been running reliably and producing commercial products for over a year. **Figure 10** and **Figure 11** show some examples of features printed on these machines using the above described gray level techniques.

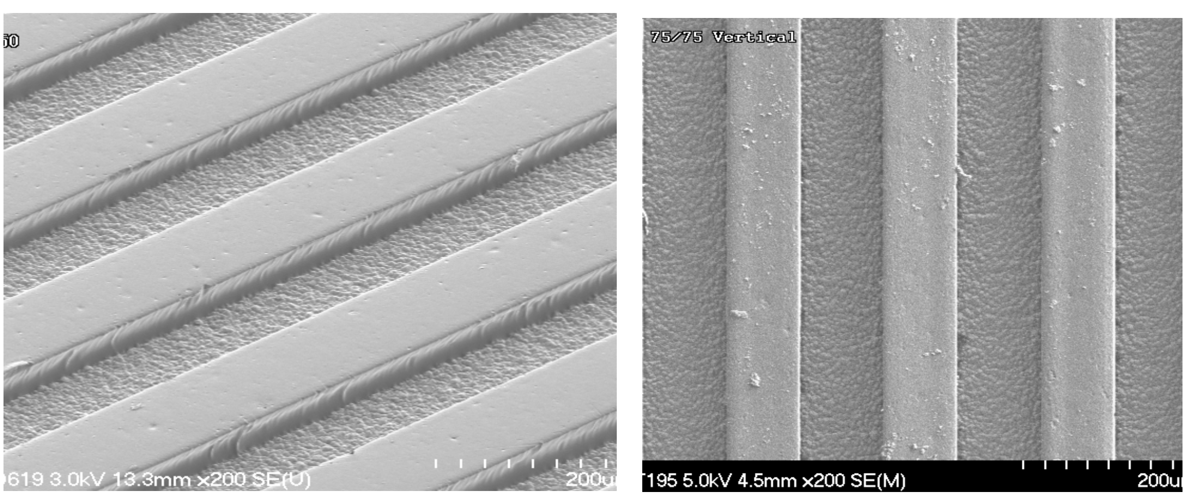
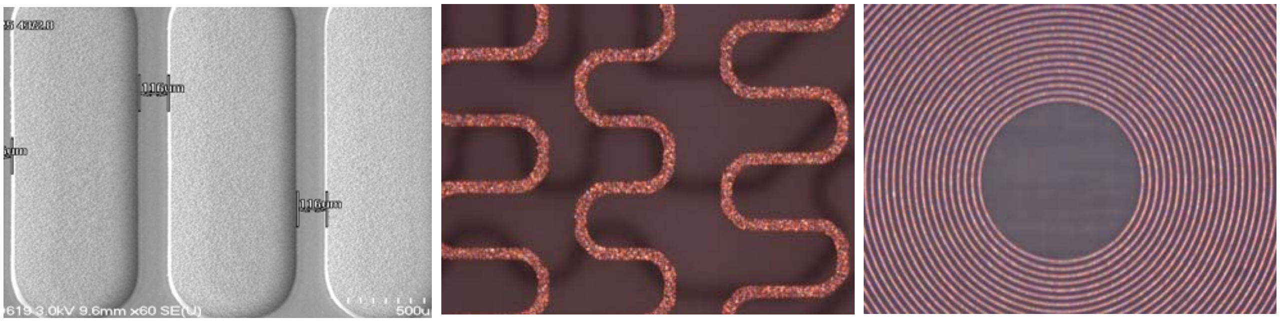



**Figure 10** SEM images of developed resist printed on MLI machine. The grainy area is underlying copper. The features are 75um lines and spaces.




**(a)** **(b)** **(c)**

**Figure 11** Images of circular and curved features printed with gray level imaging. Smooth curved or diagonal edges are difficult to achieve with conventional, dot matrix digital techniques, which often suffer from "pixilated" edges. With these techniques the solution to this problem might be to print with more dots and smaller dot spacing, resulting in slower throughput or higher data rates. Gray level imaging, with its practically "gridless" edge registration, does not suffer from this limitation. (a) SEM image of developed resist, curved test feature (b) Serpentine copper impedance control features (c) Circular copper test feature.

## 5. FUTURE APPLICATIONS

Although this paper describes an application specifically for the digital lithography of printed circuit boards, the patented gray level technique[1] described herein is not limited in application. There are many other areas where its advantages in writing speed, accurate registration, and simplified optics may be beneficial. These include chip packaging, solder mask patterning, the fabrication of MEMS devices, lens arrays, diffractive optical elements, and flat panel displays, and even the printing of newspapers and magazines. Currently, the operation of Texas Instruments micromirror arrays is limited to a shortest wavelength of about 280nm in specialized versions of the chip, so that these devices can not yet be employed for the most advanced semiconductor lithography using sub 200nm wavelengths. But with continuing advances in micromirror devices, as well as light sources such as LEDs, the range of applications for this technique will grow.

## 6. SUMMARY

Digital, or maskless, lithography systems are rapidly being adopted by the PCB industry to meet ever increasing demands for tight registration. A novel digital technique for the production of printed circuit boards has been described herein. It is based on the commercially available digital micromirror device (DMD) from Texas Instruments, which is used widely in DMD-based digital projectors and HDTVs. A unique and patented gray level imaging technique[1] allows the tight registration called for by the PCB industry to be met with relatively large projected mirror, or pixel sizes. This means that fewer projected mirrors are printed per unit area, allowing for faster write times than conventional digital techniques based on dot-matrix or binary pixel printing. The main advantage of digital printing, the custom scaling of pattern data to match underlying features, is thus retained with high panel throughput. This technique is not limited to PCB, but can be applied to any area of printing or lithography requiring high throughput and tight registration

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