Flexible Electronics and Displays: High-Resolution, Roll-to-Roll, Projection Lithography and Photoablation Processing Technologies for High-Throughput Production

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Invited Paper

Flexible electronics are increasingly being used in a number of applications which benefit from their low profile, light weight, and favorable dielectric properties. However, despite these advantages, the range of practical, high-volume, applications for flexible electronics will remain limited in the future unless a number of challenges related to lithographic patterning on flexible substrates are successfully addressed. The most critical of these pertain to system parameters that affect the cost and performance of flexible circuits, including the resolution, panel size, process throughput, substrate distortion, material handling, and yield. We present a new class of roll-to-roll lithography systems, developed in recent years, that were designed to address the challenges in each of these critical areas. These systems provides high-resolution projection imaging over very large exposure areas, on flexible substrate materials. Additionally, they achieve high-precision alignment by means of image scaling to compensate for substrate distortion due to processing; and they also performs high-throughput photoablation, patterning millions of pixels simultaneously, by means of projection imaging. This technology is attractive for current and emerging applications, such as flexible circuit boards and flexible chip carriers, as well as for potential future applications such as such as flexible displays and macroelectronic systems.

Keywords**—***Chip carriers, flexible circuit boards, flexible displays, image scaling, large-area exposure, macroelectronics, photoablation patterning, projection imaging, roll-to-roll lithography, seamless scanning.*

I. INTRODUCTION

The rapidly increasing demand for high-performance, highly compact and portable devices, along with the significant manufacturing advantages of roll-to-roll processing, have spurred the growth of flexible chip packaging, flexible interconnects, and flexible circuit boards. Flexible materials offer lower profiles, lighter weight, more compact end-products, and, often, better performance. For example, typically based on thin-film polymers of the order of 25–200 μm thick, flexible electronic materials are thinner and lighter than reinforced epoxy circuit boards. Additionally, flexible interconnects enable the development of highly compact electronic packages (e.g. portable video cameras, automotive electronic systems, and medical equipment) with little "empty" volume, by allowing for the use of discrete electronic modules connected by flexible strips that can be conformed to the irregular contours of the unit. Further, in applications where speed is critical, such as for chip carriers, the relatively low dielectric constant of organic substrates offers better performance, compared with ceramic chip carriers. We note that for many current interconnect applications, the flexible modules typically contain interconnects on either one or both sides of a single-layer substrate, and for today's most advanced chip carriers—which must mate the high-density interconnects on silicon chips to the lower density connections used on circuit boards—the flexible substrates may consist of up to three or four layers, with line features currently as small as 15 μm, and down to 10 μm within a few years, according Sematech's International Technology Roadmap for Semiconductors.[1] The manufacturing requirements for these substrates are demanding, and the cost of the substrate therefore often exceeds the cost of the chip that is attached to it [1].

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While the demands for higher performance, lightweight, portable systems has spurred the development of flexible electronic packaging, these same needs have driven the flat-panel display (FPD) industry to pursue the development of active control circuitry on flexible substrates, with the promise of thinner and lighter thin-film transistor (TFT) backplanes. Current glass-based liquid crystal display (LCD) backplanes are patterned at critical dimensions of 3–5 μm, and TFT backplanes-on-flex would call for similar requirements. In addition to the advantages of thinner and lighter LCD displays that will result from flexible TFT backplanes, roll-able displays will be possible when flexible backplanes are used to drive organic light-emitting diode (OLED)-based displays [2]. With even higher levels of integration, TFTs, OLEDs, and all supporting electronics may be fabricated on a single flexible substrate material—a monolithic electronic system. Further extensions of this monolithic fabrication technology will eventually usher in the era of macroelectronics, when integrated circuits, microelectronic mechanical systems (MEMS), and microoptical electronic mechanical systems (MOEMS) devices, fiber optic communications links, microfluidics, etc., will all be fabricated on a single monolithic flexible substrate material.

In addition to the performance advantages offered by flexible substrates, manufacturing techniques based on roll-to-roll processing (also widely called web processing) of flexible substrates can provide many cost benefits, including reduced contamination and thus better yield, higher speed automation, and reduced overhead time [2]. Unfortunately, the full advantages of better yield are not fully realized when contact printing techniques are used, as a result of the yield loss due to mask-substrate contact or proximity. In contrast, projection printing—in which the mask is imaged onto the substrate by means of a projection lens—results in excellent yield since the mask and substrate are never in contact.

While projection printing offers the significant advantages of high yield, as well as high-resolution, projection lithography systems in the past have been developed primarily for integrated circuit manufacturing applications, where submicrometer resolutions are required. Thus, new generations of technology have achieved higher resolutions, compared with the previous technologies—but they have not been designed for large-area patterning, nor for flexible substrates, thereby limiting their use to the exposure of areas several centimeters in dimension, on rigid substrates.

The challenges of projection lithography on large-format substrates are inherently different from those of integrated circuit (IC) fabrication, and, therefore, they cannot be met efficiently by various attempts at modifying and adapting, for large-area lithography, the tools that were primarily designed for ICs. The key performance criteria of resolution, alignment precision, depth-of-focus, substrate size and cost-of-ownership require different considerations for ICs (which are patterned by repeating a single pattern many times over the area of a large wafer) and for large format circuits, which are much larger than chips. Large format circuits cannot be segmented into smaller modules or die during fabrication, but, rather, must be patterned as a single, monolithic large-area unit, calling for unique design considerations for the imaging system, the mechanical sub-systems, and the alignment system of the lithography tool. These challenges, which are addressed by our large-area projection lithography system technology, have been discussed in a previous paper by us [3]. In this paper, we focus on the challenges of projection lithography on flexible substrates, keeping in mind that the substrates may range in size from several centimeters, up to many meters.

Herein, we first discuss several critical manufacturing processes related to the patterning of high-resolution features (ranging from 1–20 μm) on flexible substrates. We then review a system technology that is attractive for fabricating flexible electronics, and we give examples of results achieved with this technology. Finally, we discuss future directions, with a focus on macroelectronics.

II. FLEXIBLE ELECTRONICS KEY MANUFACTURING TECHNOLOGIES

A. 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 and proximity printers, as well as steppers, are, for large-area applications, at the end of their capabilities. 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 $\sim 25\mu$m features, they are unlikely to provide large-area lithography capability at the 5-μm level, and much less at 1 μm, on panels exceeding several inches in dimension. 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, since they are typically limited to field sizes of a few centimeters. Finally, and most importantly, it is increasingly being appreciated that critical performance parameters—such as resolution, substrate size, alignment precision, depth of focus, and cost of ownership (which is a composite figure of merit that takes into account throughput, yield, system price, operating costs, etc.)—are uniquely different for large-format patterning systems, in comparison with small-area patterning systems such as those used for IC fabrication.

B. Roll-to-Roll Lithography on Flexible Substrates

While the benefits of lower profiles, lighter weight, and more compact end-products, make flexible electronics highly attractive in terms of performance, it is their favorable cost of manufacturing that makes flexible electronics practical for integration with a wide range of products. This cost advantage may be attributed to roll-to-roll manufacturing techniques (also widely called web processing), which are based on the batch processing of continuous rolls of flexible material, up to many hundreds of feet in length. Roll-to-roll batch processing offers a significant advantage compared with the processing of discrete panels, as it increases throughput by allowing for greater levels of automation and by eliminating the overhead time involved in loading and unloading panels into lithographic imaging tools and chemical processing stations. Additionally roll-to-roll processing leads to lower contamination levels, and thus higher yields due to the minimal human handling that is needed to process the substrates. Furthermore, the nonexposure overhead time is minimized since the load and unload operations are simultaneous and simpler, compared with those used for discrete panels.

While the advantages of roll-to-roll patterning are highly attractive, careful attention must be given to the roll handling system in order to maintain a smooth, clean substrate surface—which is an absolute necessity for lithographic processing. For example, static buildup on the substrate can lead to the collection of dust and particulates on the surface, which ultimately cause a reduction in yield. Thus, ionizing air showers and reliable cleaning techniques are critical components of a roll-to-roll production line. Additionally, the flexible substrates may become stretched, kinked, dimpled, or scratched during unwind and wind. While these defects would surely render unusable the areas of the substrate where they occur, they may also result in the loss of an entire panel due to poor mask-substrate contact if contact printers are used. Similarly, the vacuum hold-down structure, which maintains the flexible panel in position during the imaging step, must be smooth and flat to ensure that the substrate remains within the depth-of-focus of the patterning system, as a flexible substrate will easily conform to vacuum grooves or scratches in the hold-down structure, resulting in poor imaging.

C. Photoablation Patterning

As discussed in the previous section, one of the benefits of roll-to-roll lithography is the high throughput that can be achieved by means of web processing. It should be noted however, that the benefits of high throughput lithography can be fully realized only if all of the steps in the fabrication process are performed at high throughput rates, that is, so long as there are no bottlenecks. We thus emphasize here that in comparing the processes that are used for material removal on flexible substrates, to create lines and vias—processes including laser photoablation, reactive ion etching (RIE), thermal laser drilling, and mechanical drilling (only used for vias)—photoablation can be significantly faster than both RIE and drilling, and more clean and precise than laser thermal drilling. Later in this paper we describe a large-area photoablation technology that patterns clean, high-resolution features at patterning rates significantly faster than both RIE and mechanical drilling systems.

Photoablation is a lithographic process which allows for the patterning of high-definition features, without the need for photoresists and the associated chemical processing. In addition to the advantages of fewer manufacturing steps, the elimination of wet processing reduces the problem of substrate distortion, which we discuss in the following section.

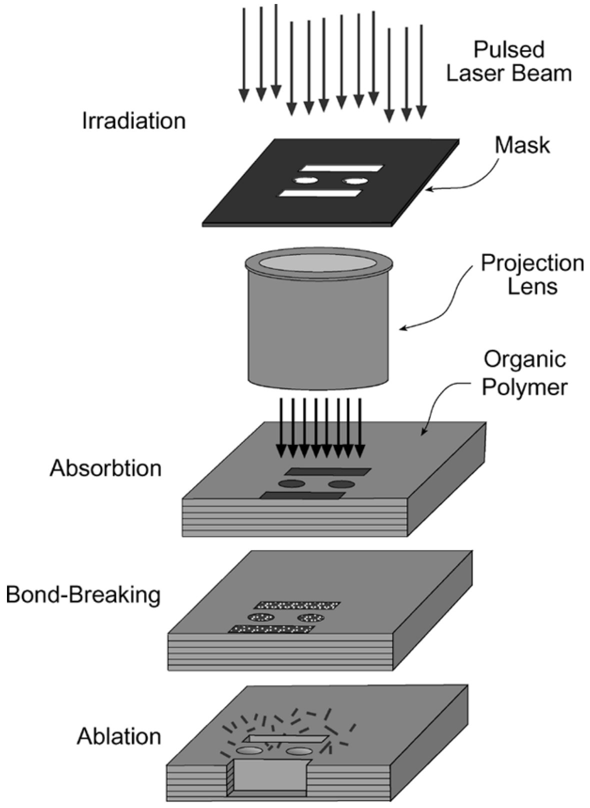


Fig. 1. Illustration of photoablation mechanism. UV light causes bond breaking in the polymer, fracturing the long-chain molecules into smaller units; the molecular fragments are kinetically ejected from the substrate. This figure is based on a drawing appearing in [5].

Before continuing, we first emphasize the distinction between thermal ablation—which is performed by melting or vaporizing material using high-power-density infrared radiation—and photoablation, which results from nonthermal, photochemical ultraviolet (UV)-induced molecular bond breaking. Whereas thermal ablation may result in a large heat affected zone, characterized by the appearance of melted material and burring around the rim of the ablated region, photoablation typically results in essentially clean features, with minimal or no material buildup in the ablated region.

The photoablation process is illustrated in Fig. 1 [4]. As seen in the figure, the illuminating pulsed UV radiation is absorbed within the skin depth of the polymer, typically of the order of a micrometer. The UV radiation dissociates chemical bonds in the long chain molecules which constitute the polymer, fracturing the molecules into smaller units. The excess energy, i.e., any incident energy which does not result in photodissociation, is transferred to the small molecular units through various absorption processes, and—so long as the energy density of the illumination pulse is above the threshold energy for the polymer material—the molecular units are kinetically ejected from the substrate.

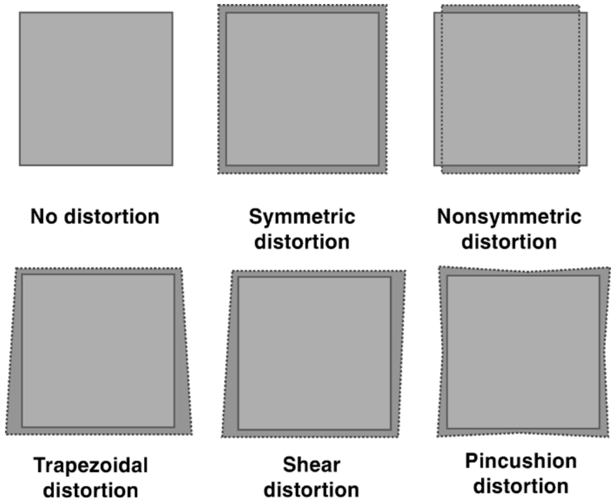


Fig. 2. Some of the common shape distortions that arise during processing of substrates for electronic modules.

The amount of material that is ablated depends primarily on the wavelength of illumination, the energy density of the beam, and the pulsewidth of the laser. The ablation process is, consequently, highly controllable—with the material removal depending only on the energy density for any given laser system, the ablation depth per pulse can be controlled to better than 0.1 μm. Examples of ablatable polymer materials that are commonly used for flexible electronics are polyimides (e.g. Kapton), PET (e.g. Mylar) and liquid crystal polymer (LCP). We review selected ablation results later in this paper.

D. Anamorphic Image Scaling

In the manufacturing of many large-area electronic devices on flexible as well as rigid substrates, the substrates undergo several processing steps that can cause the boards to expand or contract asymmetrically. Such distortion arises from exposure to elevated temperatures, mechanical stresses from handling and changes in surface material compositions. For example, for copper-laminated flexible substrates, there is always residual surface tension present between the copper film and the substrate. This residual stress may be released upon the removal of the copper through etching, resulting in dimensional changes and substrate warpage. Furthermore, flexible substrates are often processed under tension, in roll format, making it particularly difficult to manage and accurately control changes in shape that occur as a result of processing. As a result of these, and other processing effects, flexible printed circuits can often exhibit dimensional changes greater than 2000 ppm (0.002%), a variation in point-to-point distances of up to 1.2 mm for a 460 × 610 mm board! We note that rigid substrate materials, such as glass for FPDs, also undergo dimensional changes as a result of processing, and thus scaling is important for large-area lithography on rigid substrates as well. Fig. 2 shows some of the typical substrate distortions that may occur in practice.

Substrate distortion is particularly problematic given the need for higher speeds, greater functionality, and higher densities in multilayer electronic systems such as high-density interconnect circuits, RF circuits, and optoelectronic backplanes, which places greater demands on the design and manufacturing of both rigid and flexible printed circuit boards. Additionally, the drive to lower costs has continued to place extreme pressures on fabricators to improve process yields. Improved layer-to-layer registration for higher performance and yield has been identified as a high-priority technical need in the industry [6]. In the case of RF circuits, the better the front-to-back alignment, the higher the performance of the overall circuit. In the construction of optical interconnects, micrometer-level alignment is required in order to minimize planar waveguide transmission losses.

One of the major barriers to improving alignment, however, is the problem of board dimensional stability. In the past, there have been three basic ways to compensate for process-induced substrate distortion. 1) The distorted board is measured prior to exposure and a compensated glass mask is fabricated—this process can be time-consuming, and may add thousands of dollars in mask costs on a per layer, per part basis if glass masks are used. While film-based artwork is much less-expensive to manufacture, it is prone to changes in size due to temperature or humidity variations. 2) Laser direct write patterning is used to compensate for any dimensional changes—however, this manufacturing technique is severely limited in throughput due to the serial writing of each pixel. 3) Symmetric scale compensation, i.e., magnification or demagnification of the image by the same factor in the x- and y-dimensions—while this technique has been used in steppers for some time, it is limited in effectiveness given that the actual substrate changes may not be symmetric.

Later in this paper we describe a newly developed technique that allows for anamorphic X-Y scale compensation providing independent correction of board dimensional changes in the x- and y-dimensions, while maintaining high processing throughput. Additionally, through the use of dynamic scale compensation, this technique enables the correction of higher order shape distortions, such as trapezoids, parallelograms, and pincushions.

III. FLEXIBLE ELECTRONICS LITHOGRAPHY AND PHOTOABLATION SYSTEMS

A. Technology Overview

Fig. 3 illustrates Anvik's large-area roll-to-roll lithographic patterning technique for fabrication of flexible electronics. [7]–[12] This technology enables the patterning of 10-μm features on panels up to 1.5 × 1.8 m, and the patterning of 1 μm features on panels up to 0.6 × 0.6 m. As seen in the figure, the flexible substrate web, which is fed from a supply roller, extends across the exposure region on the scanning stage, and is wound onto a take-up roller. The take-up and supply rollers maintain a metered amount of slack in the roll material on either side of the patterning region. As the stage scans along the y-direction during exposure, the slack on one side of the stage decreases and is

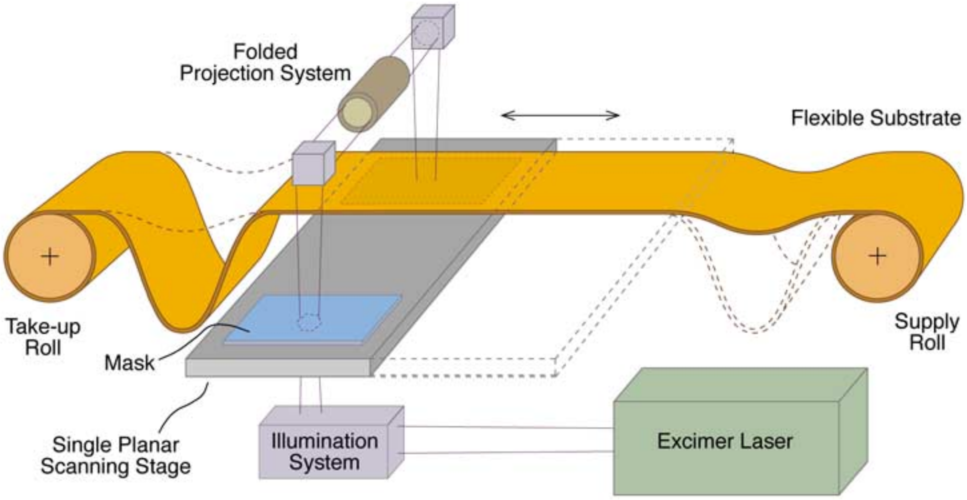


Fig. 3. Schematic of Anvik's large-area high-throughput roll-to-roll patterning system. The substrate and mask are mounted rigidly on a single planar stage, which scans the mask and substrate in unison through the object and image fields of the projection lens. Supply and take-up rollers perform the handling of the flexible web, and slack loops eliminate creasing of the substrate.

added to the slack on the other side of stage, thus preventing any stress from being transferred to the flexible material, and eliminating the possibility of any creasing or kinking of the substrate during scanning. Additionally, we note that during exposure, the segment of the flexible substrate that is being exposed, is held rigidly on the scanning stage by a vacuum diffuser. The diffuser is a flat, smooth, porous material and thus there is no deformation (ex., dimpling) of the substrate during vacuum hold down. After the exposure of a panel is complete, the vacuum chuck releases the substrate, and the flexible web is advanced to expose the next segment of the roll material.

A uniform-dose, high-resolution exposure is achieved over the full area of the panel on the flexible substrate by means of Anvik's large-area seamless scanning patterning technique. Referring again to Fig. 3, which illustrates this technique, the substrate and mask are mounted on a single planar stage, which moves the substrate and mask together in both x- and y-directions. The illumination system utilizes an excimer laser source that is coupled to optical elements which transform the nonuniform rectangular output beam of the laser into a highly uniform ($<5\%$ variation) hexagonally shaped beam that illuminates the mask. A 1:1 projection lens images the portion of the pattern that lies within the illuminated hexagonal region on the mask, on to the substrate. The projection lens has an image field of 10–50 mm in diameter, depending on the resolution of the projection lens.

The single planar stage moves the mask and the substrate in unison (say, along the x-axis), while scanning the mask through the hexagonal illumination region. Following a scan, the stage moves along the orthogonal direction (y in our example) by the effective scan width w (see Fig. 6). The substrate and mask are then again scanned along the x-axis as before, after which they are stepped along the y-axis, and the process is repeated until the entire substrate is exposed. Assuming an idealized, perfectly uniform hexagon, the complementary overlap between adjacent scans is such that the transition from one scan to the next is totally seamless and free from any exposure nonuniformity. In practice, any variations in the uniformity are less than a few percent, and can be attributed to the inherent characteristics of the excimer laser and the illumination system. Fig. 4 illustrates the mechanism of seamless overlapping scanning in more detail. The hexagon 36 represents the illuminated region on the substrate. The scans along x are shown as scan 1, scan 2, and scan 3. The movement along y after each x-scan is given by $w = 1.5\ l_h$, where l_h is the length of each side of the hexagon. As seen in the figure, the transition from scan 1 to scan 2 is seamless in exposure uniformity because the doses provided by hexagons 36 and 38 are complementary in the overlapping region, tapering to zero at apex a and apex d, respectively; likewise for scan 2 and scan 3 [3]. We remark that the dose uniformity is insensitive to small errors in the placement of the hexagons of adjacent scans, given that the dosage profiles taper to zero in opposite directions. For example, for a typical Anvik system, a 1-μm placement error—which is much larger than the errors that would realistically occur with a servo-controlled linear stage—would result in a dosage variation of $<0.2\%$.

B. *Photoresist Exposure System*

Fig. 5 shows a roll-to-roll lithography tool that Anvik has built for patterning on large-area flexible substrates in a roll-to-roll format, for fabrication of flexible electronics. As seen in the figure, the flexible substrate—which in this case is copper-on-Kapton—is fed from a supply roller, extends across the exposure region on the scanning stage, and is wound onto a take-up roller. Table 1 shows the specifications for the system.

The exposure source for this system is a XeF excimer laser, which emits high-power radiation at 351 and 353 nm. This wavelength of illumination is compatible with i-line resists, which, although optimized for the 365-nm spectral region, typically have broad-band sensitivity, ranging from below

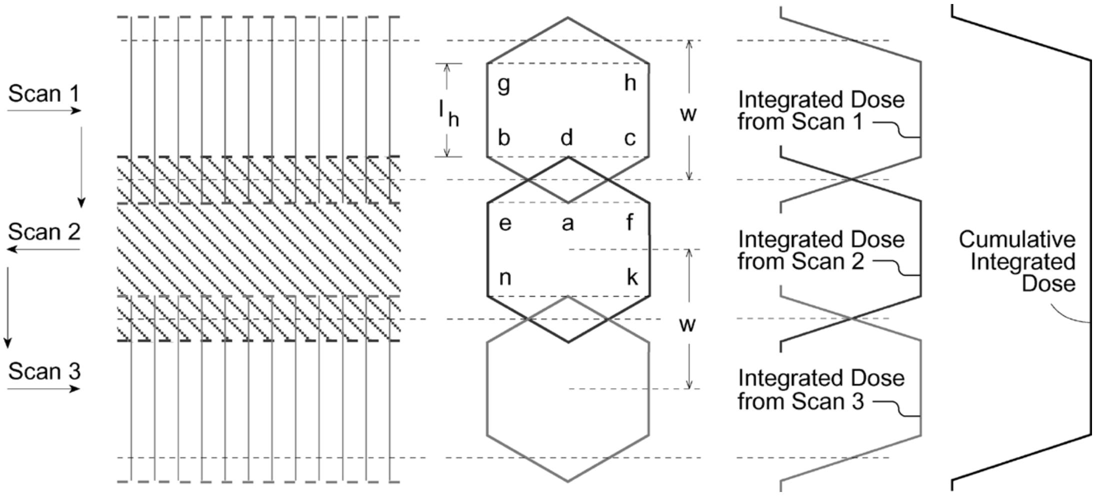


Fig. 4. Seamless scanning technique, showing the complementary exposure in the overlapping areas of adjacent scans.

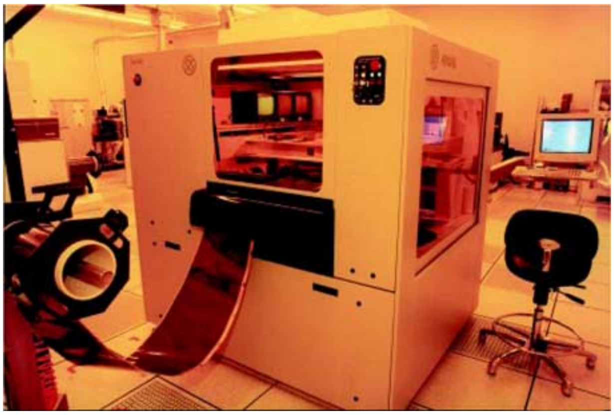


Fig. 5. Roll-to-roll lithography tool that is capable of 10-μm resolution on flexible substrate materials. The system in the photo is patterning a copper-on-Kapton substrate.

Table 1
Specifications for the System

Roll-to-Roll Lithography System Specifications	
Imaging Technique	Seamless scanning projection
Resolution	10 microns (0.4 mil)
Projection System	1:1 magnification refractive lens
Depth of Focus	560 microns (22 mils)
Lens Field Size	50 mm diameter
Substrate Exposure Area	300 x 300 mm (12 x 12 inches)
Exposure Source	XeF excimer laser
Exposure Wavelength	351 nm
Alignment Precision	± 2.5 microns (0.1 mil)
Alignment System	Automatic
Substrate & Mask Handling	Automatic
Exposure Throughput	120 panels / hr (6 sq. ft. / min)

350 nm up to approximately 450 nm. Thus, the wide array of dry-film as well as liquid i-line resists may be used with this system. The projection lens, which is color corrected over the full bandwidth of the XeF laser, achieves a diffraction-limited resolution of 10 μm over a field size of 50 mm. The depth of focus of the lens is approximately 560 μm, ensuring that focus is maintained over the entire surface of the flexible substrates, which can have thickness variations of tens of micrometers due to the build-up of multilayer stacks as well as the use of dry-film resists. The single planar stage is an air-bearing x-y scanning stage with a top scan speed of 400 mm/s, and a range of travel large enough to cover the 12 × 12 in. substrate area. The stage is equipped with an optical encoder, enabling fine control over the stage position and velocity. An alignment system ensures a layer-to-layer overlay accuracy of ± 2.5 μm by means of a pattern recognition-based image processing system that views alignment marks on the mask and substrate, and a fine positioning stage that moves the mask into alignment with the substrate, based on feedback from the image processing system. All of the subsystems—the laser, scanning stage, alignment system, and the web-handling hardware—are controlled by means of a PC-based master control interface, enabling the user to set up recipe files that automate the exposure, based on the panel layout and the resist sensitivity.

C. Photoablation System Design Parameters

While the system described in the previous section was designed to perform exposures on resist-coated substrates, other systems we have developed are capable of photoablation patterning, a one-step process that eliminates the multiple processing steps required for resist exposures. As described earlier, photoablation is a nonthermal process that allows for highly controlled material removal, enabling the high-resolution patterning of features with micrometer-level resolution, and submicrometer feature-depth control. The fundamental design of Anvik's photoablation systems is the same as that of our large-area resist exposure systems, as described above. With that in mind, we emphasize here the advantage of the large-area illumination beam; in particular, all of the image pixels within the hexagonal exposure area are patterned simultaneously, and thus, for example, a 10-μm-resolution system with a 25-mm hexagonal field, would ablate 4 million pixels simultaneously. This is in contrast to direct-write systems that ablate pixels one at a time.

The primary difference between Anvik's photoresist exposure system and the photoablation system is the working wavelength and the power density of the hexagonal exposure beam, which must be above the ablation threshold of the material. Typical energy densities for resist exposure are of the order of 10 mJ/cm^2, whereas typical energy densities for photoablation are of the order of 100–500 mJ/cm^2, depending upon the material. The higher energy densities required for photoablation demand higher power excimer lasers—as compared with those used for resist exposure—in order to maintain high processing throughputs. Additionally, due to the high energy densities, more demanding optical coating specifications and design configurations must be maintained in order to eliminate the possibility of damage to the optics.

For polymer photoablation applications, the ablation mechanism described earlier, which is based on photochemical bond breaking, suggests that the ablation efficiency depends upon the wavelength of illumination, shorter wavelength lasers generally being more efficient. For this reason we have incorporated either XeCl (308 nm) or KrF (248 nm) lasers into our ablation systems, rather than XeF (351 nm) lasers. It should be remarked here that the photon energy at 351 nm is 3.53 eV, which is less than the energy of most of the bonds commonly found in polymers, and is only slightly above the energy of the C–H bond. Thus, although the bond breaking may occur through a complex photochemical pathway, rather than by a single photon-bond interaction, we can see why XeF is not as desirable for many photoablation applications compared with the shorter wavelength excimer lasers, which have higher photon energies, and are therefore more effective at breaking chemical bonds [4].

IV. DEMONSTRATED EXPERIMENTAL RESULTS

A. *Lithography Results*

The large-area flexible-substrate patterning technology described in the preceding sections has been demonstrated on several systems that we have developed. Here we review photoresist exposure and photoablation results achieved on these systems.

Fig. 6 shows a flip chip substrate fabricated on the 10-μm resolution 3100 SRE roll-to-roll lithography tool shown in Fig. 5. Using that system, an array of these substrates was patterned on a 12 × 12 in sheet of Kapton film. The individual module shown in Fig. 6 is approximately 1 × 1 in. in dimension, and the finest features are 30-μm traces leading from the chip lead connections on the inner periphery, to the ball contacts on the outer periphery of the module.

Another example of an application of Anvik's large area flexible photolithography technology is shown in Fig. 7, which shows a frequency selective surface (FSS) fabricated on an 18 × 24 in. sheet of Kapton, sputter coated with metallic material. The FSS was designed for microwave radar applications, in particular, to selectively absorb energy over a narrow bandwidth within the microwave region of the electromagnetic spectrum, for use on radomes. The FSS was fabricated on a 10-μm resolution lithography system,

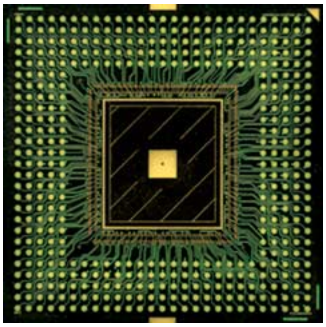
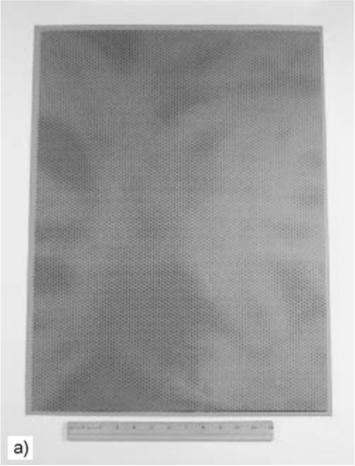


Fig. 6. Flip-chip substrate fabricated by means of roll-to-roll lithography using the 10-μm-resolution system. The conducting lines are as small as 30 μm in dimension.



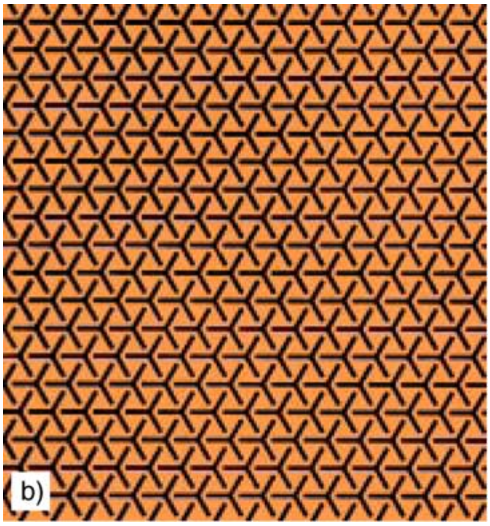


Fig. 7. (a) Frequency-selective surface fabricated on an 18 × 24 in substrate (b). Detail of the frequency selective surface. The tripole elements are approximately 10 mm in size.

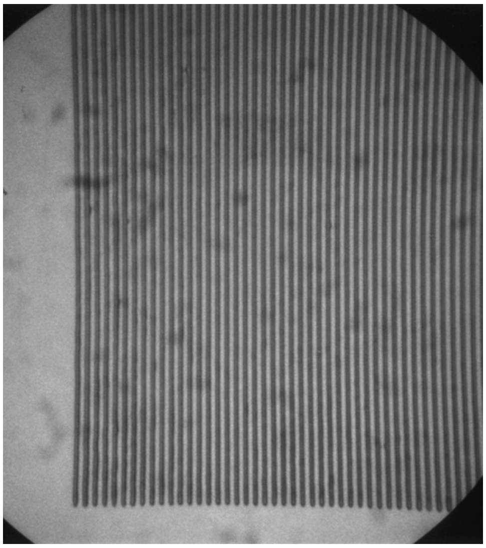


Fig. 8. 1-μm lines patterned on 50-mil-thick flexible Kapton substrate material.

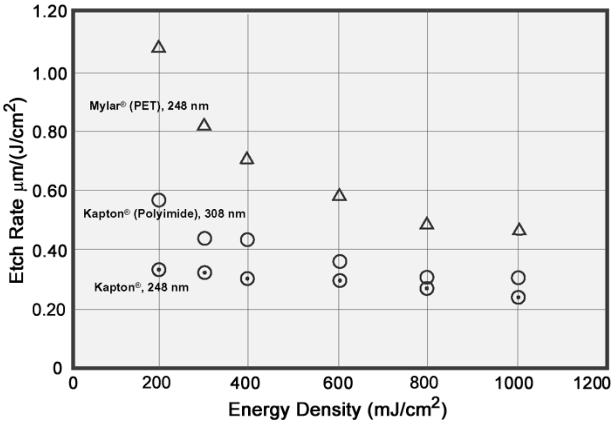


Fig. 9. Etch rates of Kapton (polyimide), and Mylar (PET) at 248 and 308 nm. The etch rate is the volume of material removed per Joule of incident energy at a given exposure energy density.

to ensure that the edges of the features were well defined, a parameter that is critical for maintaining the design specifications over the frequency range of operation. The layout of the FSS is shown in Fig. 7(b), which is a close-up view of Fig. 7(a).

We note that while the above examples were fabricated on a system that is capable of 10-μm resolution, Anvik has been developing technology to extend roll-to-roll capabilities down to 1-μm resolution and below. Fig. 8 shows 1-μm lines patterned on a 50-μm-thick Kapton substrate using the Anvik 1010 SDE lithography system, which achieves 1-μm resolution on 8 × 10 in. substrates, incorporating a line-narrowed laser operating at 248 nm.

B. Polymer Ablation Results

We show in Fig. 9 the etch rates of the common electronic materials Kapton (polyimide) and Mylar (PET), measured in our laboratory at exposure wavelengths of 248 and 308 nm. We note that the etch rate, as shown in the figure, is a valuable metric for characterizing the ablation properties of materials since it represents inherent ablatability—in particular, it is the volume (measured in μm-cm^2 in Fig. 9) of material that is removed per Joule of incident energy, at a given energy density.

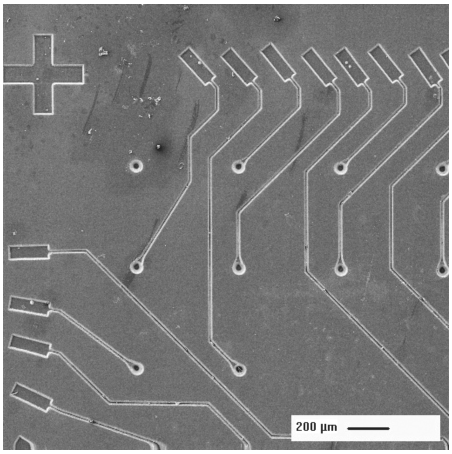


Fig. 10. High-density interconnects ablated in 2-mil-thick Kapton. The lines are 30 μm wide and the vias are 60 μm in dimension.

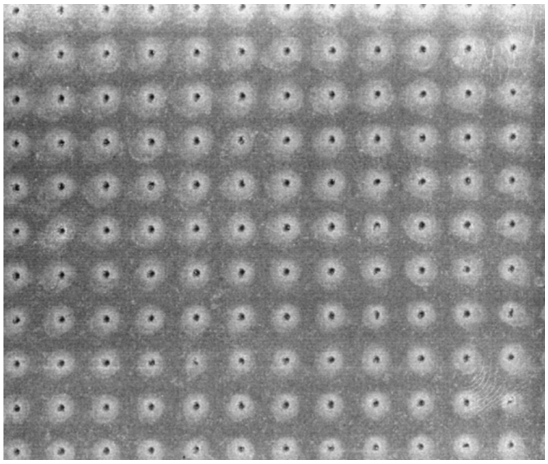
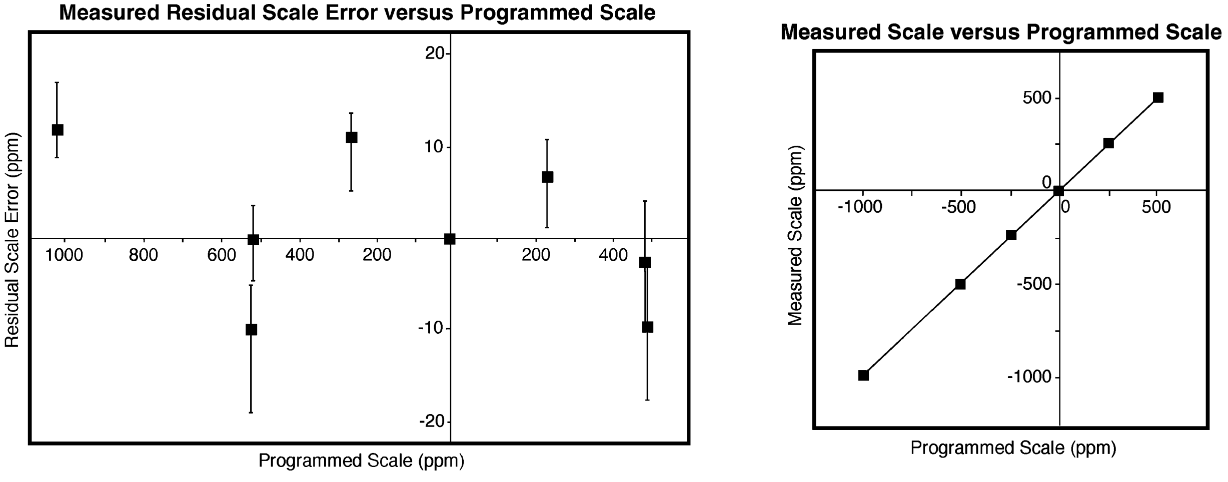


Fig. 11. 1-μm vias ablated in 25-μm-thick Kapton.

As seen in the figure, the etch rate of Kapton at 308 nm is nearly twice as high as at 248 nm, and the etch rate of Mylar at 248 nm is three times higher than that of Kapton at 248 nm. Thus, when performing large-area ablation patterning on our system at 248 nm, for a given energy density in the image plane and for a given image field size, the throughput for Mylar ablation would be approximately three times that of Kapton. We note that Mylar was not photoablatable at 308 nm. These brief examples show the importance of selecting the laser source—we have built photoablation tools operating at 248 nm as well as tools operating at 308 nm, depending upon the application.

Fig. 10 shows high-density interconnects ablated in 2-mil-thick Kapton by means of exposure at 248 nm. The pattern was ablated using a two-step process with overlay; in the first step we ablated 30-μm-wide traces with pads at the end, and in the second step we ablated 60 μm vias at the ends of the traces, aligned with a precision of ±2.5 μm. Fig. 11 shows 1-μm vias ablated in 25-μm-thick Kapton using the Anvik



(a)

(b)

Fig. 12. Scale compensation results. (a) Measured scale versus programmed scale. (b) Residual errors for selected scale settings. Scale compensations up to 1000 ppm were attained with a precision of 10 ppm and better.

1010 SDE lithography system, operating at 248 nm. An array of vias such as this would be attractive as a nozzle array for applications such as ink-jet printing and fuel injection.

C. *Image Scaling Results*

We have developed technology to perform automatic scale compensation, independently in the x- and y-directions, by optomechanical means. Initial testing of our technique was performed on a system designed to achieve ±1000 ppm scale correction, equally in the x- and y-directions. In future systems we plan to implement independent x, y-scaling, as well as variable x, y-scaling to compensate for nonrectilinear distortions, such as trapezoidal and pincushion varieties.

For our scaling tests, we used a chrome-on-quartz mask having fiducials arranged in a 4 x 4 in. x-y array. In order to eliminate the possibility of thermal expansion of the substrate affecting our tests, we used a silicon wafer, rather than a flexible film, owing to the low thermal expansion coefficient of silicon. We imaged the mask onto the substrate at scale settings ranging from 0–1000 ppm. By means of a coordinate measurement system having an accuracy of ±1 μm, we measured the fiducial separations on the mask, and on the substrate for each of the scale settings we tested. Fig. 12(a) shows the measured versus programmed symmetric scale compensation over the range of -1000 to $+500$ ppm. Fig. 12(b) shows the residual difference between the programmed scale compensation and the actual scale of the exposure. As seen in the figure, the scale was adjusted over a range of 1000 ppm with a precision of 10 ppm and better. We note that a 20-ppm error corresponds to a 2-μm shift over 100 mm.

V. EMERGING APPLICATIONS

From a historical perspective, electronic circuits on flexible substrates were initially developed for circuit board and chip interconnect applications, in order to: take advantage of the benefits of improved throughput and yield offered by roll-to-roll processing; lessen the weight of electronic packages; improve electrical performance; and allow for a reduction in system size by conforming the substrate to fit within a small space, such as in automotive applications. Recent developments in the past few years in laser crystallization and MEMS fabrication, especially in the areas of crystallization-on-flex and MEMS-on-flex are giving rise to the burgeoning field of macroelectronics [13]. In contrast with microelectronics—which are driven by the need for the smallest possible dimensions—macroelectronics applications are driven by a calling for highly integrated devices that are very large in area and/or have a flexible form factor, with nominal features in 1–10-μm regime. Macroelectronic systems include integrated circuits, MEMS and MOEMS devices, fiber optic communications links, microfluidics, etc., all fabricated on a single, flexible substrate material. We emphasize that in the vision of macroelectronics, all of these devices would be fabricated directly on the flexible substrate base material, rather than being fabricated separately as stand-alone modules that are then bonded to the substrate. Several examples of macroelectronic systems are given below.

A. *Large-Area Flexible Antennas*

Antennas fabricated in a highly integrated package on large-area flexible substrates—with all of the functional modules (e.g. control, processing, communications, and beamforming) directly integrated into the substrate material—are highly desirable since they can be rolled up into a compact package, and easily deployed into space. Especially for space-based applications, large antenna area is an important feature which would enable high sensitivity and a high degree of directionality. Reconfigurability, by means of MEMS switches would enable tuning of the operating frequency and/or changing of the radiation pattern. Additional desirable features include embedded sensor arrays to perform dynamic and static structural metrology during deployment and operation, for example, detecting any stresses, creases, and rips in the flexible substrate that may

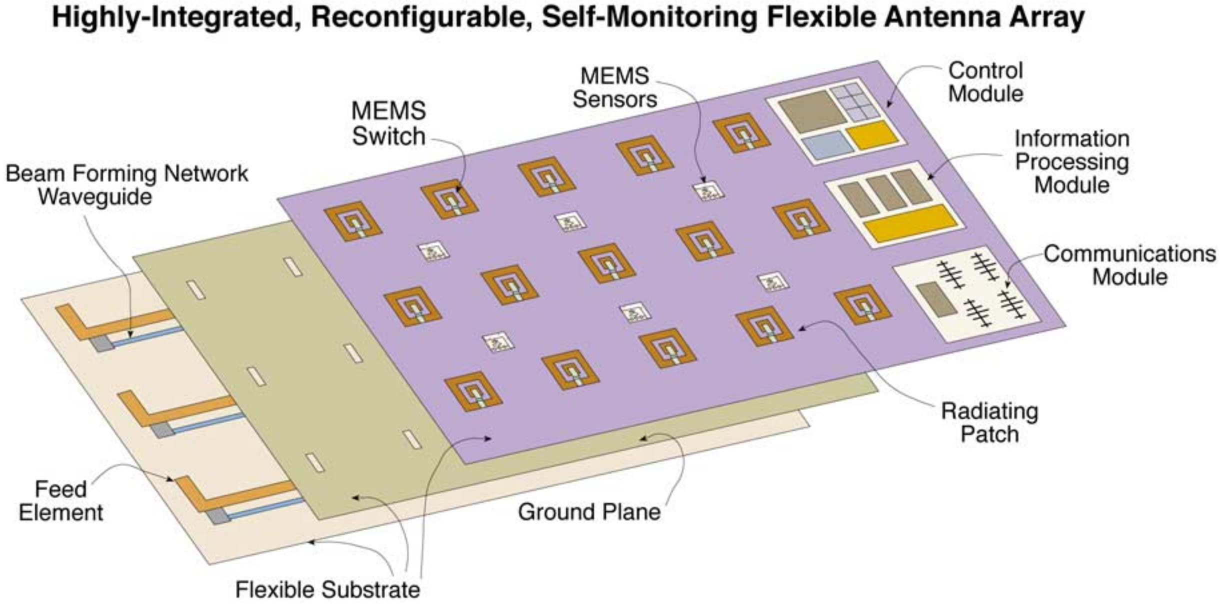


Fig. 13. Schematic representation of a macroelectronic system, a highly integrated flexible antenna array. The array contains integrated controls, information processing, and communications circuitry fabricated directly onto the flexible substrate. It also features MEMS switches and optical waveguides patterned on the substrate as well.

arise when the antenna is rolled/unrolled. A representation of a macroelectronic highly integrated antenna is shown in Fig. 13.

B. Solar Sails

Many future missions to deep space will likely be performed by means of solar sail-based spacecraft. Since solar sails accelerate by means of momentum transfer resulting from reflection of photons emitted by the sun, spacecraft with very low mass that are driven by very large sails can take advantage of the steady propulsion offered by the sun to attain speeds that are significantly higher than those achieved with chemical rockets. Thin, flexible substrate materials are well suited for solar sail applications, as they can be used to fabricate solar sails that are hundreds of meters or even kilometers in dimension, and they offer very low mass density (for example, currently available materials, such as aluminized 5-μm-thick Kapton has a mass density of 7 g/m^2). While initial missions will use solar sails attached to a payload and support systems, the long term vision is a gossamer spacecraft, in which the payload and all supporting modules are fully integrated with the ultrathin solar sail substrate [14]. For example, applying gossamer spacecraft technology to a space telescope, a thin-film membrane would function as a large aperture for observation and also as a solar sail for propulsion. Additionally, the membrane would be populated with multifunctional patches containing photovoltaics to produce power, phased array antenna elements for communications, flexible microelectronics for command and data handling, and flexible sensors.

VI. CONCLUSION

There are numerous challenges associated with performing lithography on large-area flexible substrates. These challenges relate to resolution, panel size, process throughput, substrate distortion, material handling, and yield. We presented a new class of roll-to-roll lithography systems, developed in recent years, that provides high-resolution projection imaging over very large exposure areas, on flexible substrate materials. Additionally, these systems achieve high-precision alignment by means of image scaling to compensate for substrate distortion due to processing; and they perform high-throughput photoablation, patterning millions of pixels simultaneously, by means of projection imaging. The roll-to-roll lithography technology presented in this paper is attractive for current and emerging applications, such as flexible circuit boards and flexible chip carriers, which demand fine features and precise overlay. Potential future applications include highly integrated systems on flexible substrates, such as flexible displays; and macroelectronic systems, which will include integrated circuits, MEMS and MOEMS devices, fiber optic communications links, microfluidics, etc., all fabricated on a single, flexible substrate material.

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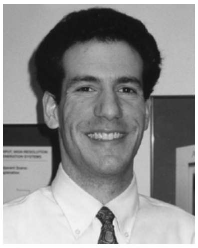

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