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DIRECT WRITE PATTERNING OF MICROCHANNELS

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ABSTRACT

Microchannel based master molds or final devices are typically produced using a series of resist deposition, exposure, development and etching steps. These steps can then be repeated to create multi-layer fluidic structures. Traditional fabrication of these devices requires the use of a physical mask for the photolithographic exposure process. In the research and development environment, where designs are constantly undergoing changes, or in rapid time to device applications, this can be a costly and time-consuming practice.

We have employed a novel micron-scaled resolution, maskless photoimaging/patterning tool that permits the creation of small, arbitrary features. This microdevice printer is useful for constructing fluidic channels, devices, structures and packages, utilizing any photoimageable or photoreactive material that can be applied towards fabrication of integrated microfluidic-based systems. The fabrication technology can provide features down to 10 microns simultaneously over a 2x2 cm^2 field of view. Additionally, applying manual stitching techniques can yield unlimited field of view for large area fluidic patterns with high-resolution elements.

The instrument relies on the use of microoptics and spatial light modulation to create the required 2D pattern aerial image for photoimprinting. The instrument creates mask free designs on planar and curved surfaces and has been applied to a variety of materials, including metals, ceramics, organic polymers and semiconductors. We have demonstrated the utility of the instrument for creating mechanical, optical, fluidic and electronic components and combinations that would form the basis of integrated microfluidic systems, microanalytical systems and micrototal analysis systems (uTAS). We have also applied the instrument to creating fluidic channels having structures integrated within the channel geometry. The technology has widespread applications in the MEMS, bioMEMS, microcooling technologies and sensor markets. A further extension of the technology is the application of the direct printer to rapid prototyping of microchannels and minichannels for fuel cells, microrefrigerators, heat exchangers, and biomedical devices.

MICROCHANNELS/MINICHANNELS

Microchannel Phenomena

Channel architectures are almost universally found in complex natural and synthetic systems. Channels exist as waveguides, particles guides, and circuits and can be found in both raised and recessed forms. Although channels can be used for theoretical illustrations, such as the channel capacity in an information system, channels are practical solutions to efficiently routing physical particles (electrons, ions, molecules, photons etc…) from a source to a destination. We have been interested in applying the channel fabrication capacity of mask free patterning, which is in essence a versatile channel network construction system, to the practical problem of making a large variety of functional circuits for devices that utilize mechanical waveguides, electrical circuits, optical waveguides, and mass-flow fluidic channels.

Channels that are reduced in size can be classified as microchannels when they range from 1 um to 1000um. Within this micron regime, the physical phenomena mentioned above (mechanical, electrical, optical, and fluidic circuits) have variable optimal size/performance/cost features. For example, microfluidic circuits below 30 um, used for fluid transport in lab on chips and microreactors, have significant resistance to flow and require more exacting particle filtration at the same time only yielding moderate dividends in chip real estate. In addition to the increased flow resistance, at sub 30 uM dimensions there exist an increased cost for finer dimensional control. Electrical circuits in contrast yield increased performance with smaller dimensions and warrant the increased cost associated with their manufacture. However, even electrical circuits have applications, for example in packaging, where channel sizes are micron to millimeter in scale.

Microchannel PhotoPatterning

Although there exist manifold new ways to create microchannel patterns; embossing (Emmelius), imprinting (Chou), soft lithography (Xia) inkjet (Hayes) and laser direct write (McClelland), photolithography remains the most popular method for defining and creating microchannels features. However, to date most photolithographic routes require physical masks and can be very expensive tools. Direct patterning of channels in different photoreactive materials using electronic masks presents an new opportunity to quickly create a wide variety of electrical and photonic circuits, mechanical acoustic waveguides , RF waveguides and gas or liquid flow channels. As important, an electronic mask technique permits an easier route to fabricating multilayer channel systems (i.e. 3D systems) that can be made as a composite of the variety of circuits mentioned above. When such a patterning technique is combined with post pattern transfer processes (electroforming, vapor deposition and etch, etc…) and applied to a variety of polymers, metals, ceramics and glasses, an accessible toolbox for creating functional channel systems and packages becomes available.

Taking fluidic-based multilayer systems as an example, most required microchannels demand between 30–300 um, in two or three dimensions. Typically in two-dimensional circuits a standard binary mask is adequate for creating the final channel network. However, masks even at these dimensions carry associated costs and time for fabrication and the possibility of failure due to physical marring. For creating 3D channel networks, multiple physical masks would become cost prohibitive and be difficult to create an efficient process flow. In contrast, electronic "virtual" masks are dependent only on design cost/time and are free from fabrication penalties. Mask free fabrication appears to be the most efficient route to creating the multiple layers required in 3D systems. When combined with laminate construction methods, a variety of 3D Microsystems can be achieved using such an approach. An alternate strategy for creating 3D microsystems is the use of microstereolithography (Varadan), typically using rastered laser beams as the means to photodefine the channel features. Electronic masks can also provide a microstereolitohgraphic mode if configured with the proper mechanical and material controls creating a parallel multipoint exposure stereolithographic system. Using this multipoint exposure path is more efficient than single point rastering (i.e. laser/inkjet) since an entire plane of substrate material is exposed at once. In either mode; independent layer exposure combined with lamination or microsterolithography, the use of parallel light modulation can enable flexible, programmable and producible 2D/3D microchannel systems.

MASKLESS LITHOGRAPHIC PRINTER

The electronic mask, maskless lithographic tool used (Model SF-100, Intelligent Micro Patterning LLC, St Petersburg, FL) is equivalent to a microchannel printer. The technology utilizes reflective micro optics in combination with mixing and imaging lenses to allow direct circuit image projection onto a substrate surface. In the technique reflective microoptoelectromechanical (MOEM*)* elements are used to spatially modulate light such that light can be controlled on the several micron sized regime, simultaneously over a 2x2 cm^2 centimeter sized field of view. In addition, applying manual stitching techniques can yield unlimited field of view for large area circuit patterns while maintaining high-resolution features. The performance of the tool is similar in scale to cellular building processes where small-scale features are built up into large-scale constructions. The desired pattern is designed and stored using conventional computer aided drawing techniques and is used to control the positioning of the individual elements in the spatial light modulator to reflect the corresponding desired pattern. In addition, an alignment fixture for mounting of the substrate allows the substrate to be moved in three dimensions, providing alignment in two, coplanar dimensions and the capability to produce three dimensional structures by aligning the substrate in a third dimension perpendicular to the two coplanar dimensions. The microfabrication process can additively create microstructures of non-linear geometries. Figure 1 shows the benchtop system.

Figure 1: SF-100 Maskless Photoimaging Tool

Custom patterns are designed using any Windows based program and the screen-based image is ported to the printer through the 15 pin data port. Exposure times for different photoresist characteristics are set via timer. A microscope is used for feature registration and inspection of the exposed substrate pattern. The diagram in figure 2 illustrates this system from topview.

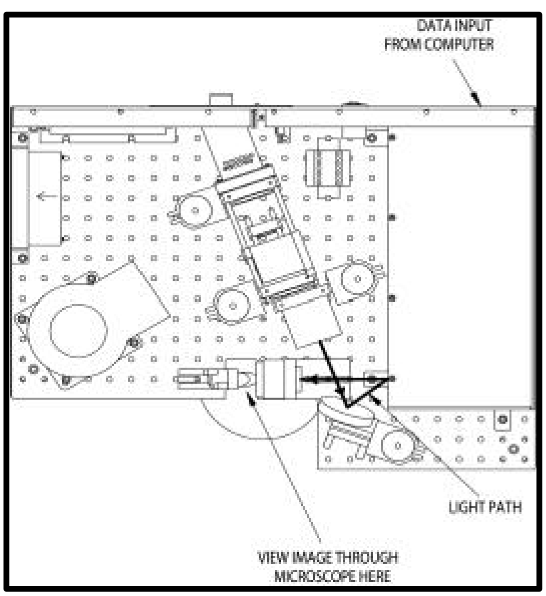

Figure 2: SF-100 optical bench layout.

We have combined the photopatterning tool with popular CAD (e.g. Solidworks) tools to permit manual and automatic generation of 2D and 3D prototypes directly from computer design. The instrument also can be further applied to creating patterned, structured layers for controlling chemical, biochemical and physical properties of surfaces.

MICROCHANNEL FABRICATION MODEL

In order to test the utility of the printer system the systems has been applied toward creating water measurement systems using PCBMEMS (Merkel, Nguyen) or Laminate MEMS based on liquid crystal polymer (LCP) and Polyimide(PI) (Fries). The PCBMEMS packages embed the various sensing elements within the LCP and Polyimide laminates. Functions are created using the direct write technology combined with both plating and etching pattern transfer processes. Figure 3 provides standard process flow for fabricating common elements within a LCP based PCBMEMS system

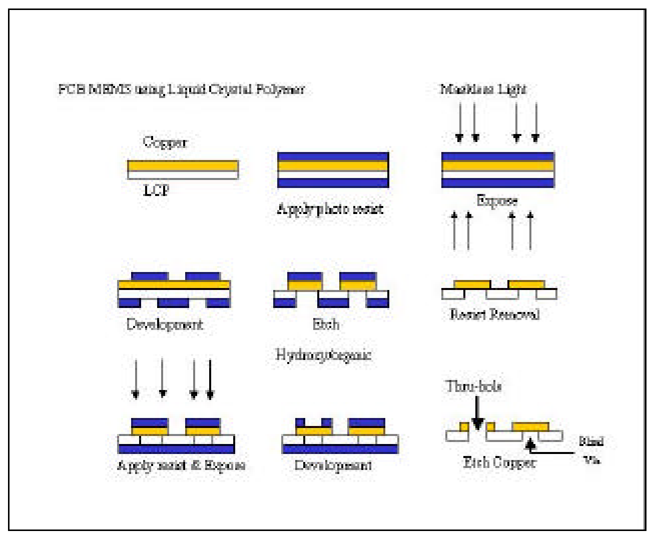

Figure 3. Process flow for PCBMEMS through-hole, blind via and microcircuit/microchannel fabrication The process flow is for LCP/Cu patterning but will be similar for other PCB materials.

MODEL FLOW SYSTEM

In order to demonstrate the power of the rapid prototyping we can propose a targeted system design with simulation or optionally removing the simulation from the requirements and follow a close coupled design-fab cycle that yields immediate parts for evaluation and process optimization.

We can use the creation of an orifice (for an example see Figure 13) for metering of material transport as a good model for this illustration. We are interested in flow control and flow sensing into various analytical modules (e.g. field mass spectrometer, or chemical color strip detectors) in order to determine chemical concentration from the registered analytical detector response and the mass based flow rate detected. In this patterned orifice we are concerned with the orifice size at which a desired mass-based flow rate will occur through the hole. We need to account for material properties of the fluid and the orifice as well as the environmentally induced imperfections in the fabrication process used to make the orifices. These variations are difficult to predict and are not yet amenable to accurate simulation.
The fundamental orifice meter mass flow equation is

$$qm = N1CdYd^2\left[\sqrt{r\Delta P / 1-b^4}\right]$$

where qm is the mass-based flow rate and C_d is the orifice plate discharge coefficient, d is the orifice bore diameter and β is the ratio of the bore diameter to channel diameter.
The orifice meter is highly dependent on the physical dimensions, for example the orifice bore diameter, the meter tube diameter and the diameter ratio (more commonly referred to as the beta ratio- β). From the relationship it is evident that small variations in physical sizes of the orifice and the tube/channel results in wide meter performance characteristics. Furthermore, any variation in these parameters effectively changes the known value of the discharge coefficient C_d, for a particular metering device.
We can expect there to be process-induced imperfections in the geometries of the device on any given day. And also when initially attempting the fabrication of an orifice device it can be an advantage to rapidly fabricate a bracketed sereies of test devices to verify initial design selections. In either case a fast prototyping capability can aid in successful device creation through close-coupled design fabrication cycles.a

RESULTS/DISCUSSION

The following results/discussion illustrates a sampling of microchannel designs that can be patterned using the photoimaging workstation. Figure 4 is a demonstration pattern for integration of features within a microchannel for fluidic control. The image shows an inlet orifice (to the left) connected via a channel to an intermediate volume containing a simple pillar array. The pillar array can be used for a variety of functions such as mixing, fluid diversion, sensing and heat exchanging. The patterns were created simultaneously but multiple exposure and depositon cycles are possible.

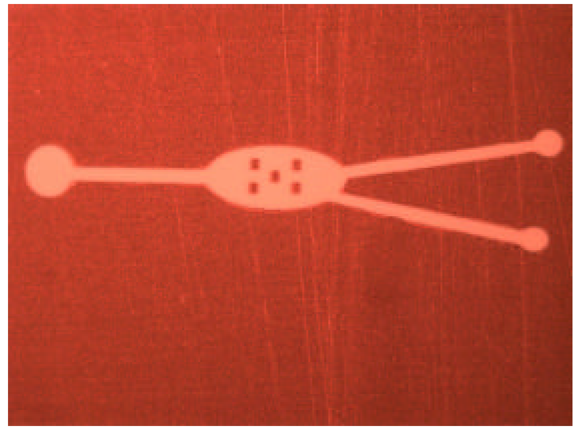

Figure 4: Features Patterned and etched inside cu clad LCP Channel using the SF-100 and ferric chloride.

In figure 5 is a heater design patterned in liquid crystal polymer/copper. The heater is a support heater module for a nucleic acid reaction amplification microreactor.

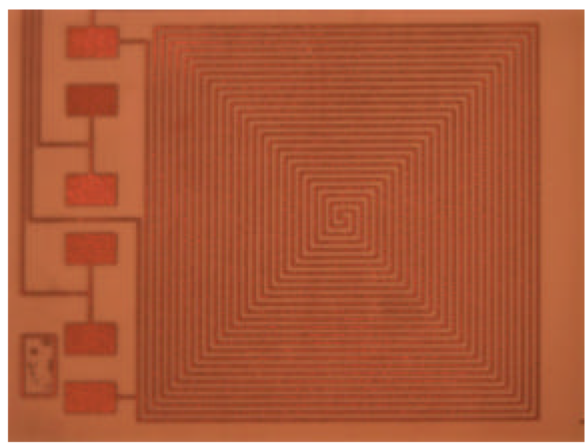

Figure 5: A circuitous heater made from Cu clad LCP material that was photopatterned without the use of a mask and etched with ferric chloride.

In addition to LCP, Polyimide comprised systems are attractive for making microchannel-based devices (Metz). Figure 6 demonstrates the application of the phototool for the fabrication of a polyimide microfluidic-based analysis chip. The fluidic microchannel is underlying the copper electrode layer. The laminate was constructed by defining then etching the fluidic channel in the bottom layer separately, from the electrodes on the upper layer and laminating the two together. The upper layer was created by printing and etching of a polyimide single clad laminate. The lower layer was made by photodefining the microchannels in a photoimageable spin-on, negative tone polyimide (HD 8000, HD Microsystems). In the right image is a commercially acquired polyimide chip that was purchased and used as a master design to replicate. The chip is provided for purposes of comparison between the two systems. Neither chip was tested for performance.

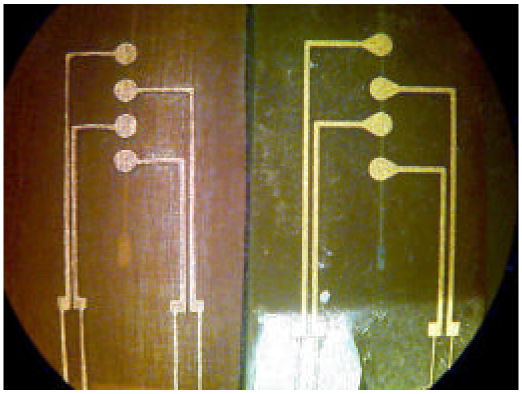

Figure 6: Polyimide system (left) made with the maskless lithographic system. The upper layer is a print and etch copper-polyimide laminate. The lower layer is a microchannel defined within a negative tone polyimide polymer. The right contains a commercially acquired chip used for comparison.

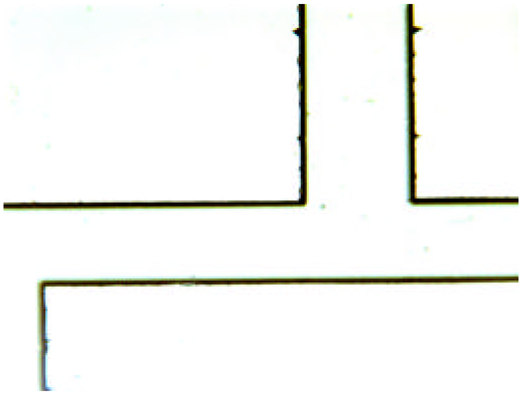

Figure 7: Microchannels patterned on glass using the SF-100 and etched with HF

An alternative to the use of polymeric materials for microchannels in lab on chips is the reliance on glass and its superior chemical properties. The channels in figure 7 were fabricated by combining photodefined resist regions with exposing the chip to buffered hydrofluoric acid etchant. The channels are approximately 10 microns deep and 100 microns wide. The channel is part of a micro flow injection manifold for injecting discrete amounts of volume in a downstream process stream.

Figure 8 shows an example of a LCP/glass/PEEK comprised micro total analysis system. The surface mounted nanoports were the only components not defined lithographically. The system contains photodefined bottom layer copper electrodes (200um) penetrating into a photodefined polymeric square (50um high) to create an electrochemical cell. The cell has a glass cover with nanoports on the top for fluid I/O.

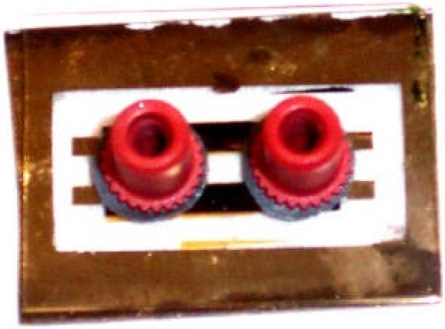

Figure 8: Micro Reactor Assembly with gold electrodes patterned using the SF-100

One limitation of the LCP/Cu flex is that it is a compliant material and it is not see through. (Yang) A path around these limitations is to use LCP/Cu bonded to glass to create enclosed volumes, which are rigid and also contain a visual window for reactor monitoring, e.g., fluorescence detection. Figure 9 exhibits micro channels within the copper film on LCP/Cu on glass. The outer channels are twice the width of the two inner fluidic circuits (30 um).

Figure 9: Micro Channels in Cu clad LCP material laminated onto glass

Another possibility is that instead of using the Cu to define the channel walls, use the LCP dielectric itself. As mentioned above, we have a process flow that incorporates a KOH etch to the LCP effectively creating channels within the LCP material itself. The low moisture absorption of LCP and the ability to form 10-20 microns features in this material make the dielectric and good substrate to create fluidic circuits.

Figure 10: Microchannels etched in LCP material patterned with the SF-100 and etched with KOH

An additional view of the resolution from the light system is exhibited in Figure 11. The material here is a copper defined channel approximately 25 um in width.

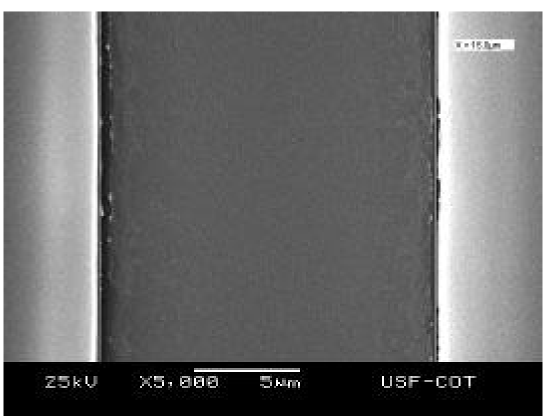

Figure 11: SEM of SF-100 Patterned Microchannel. The channel is approximately 25 um wide.

In combination with fluid channels is the use of fluid reservoirs or microwell arrays. The wells may form the basis of microreactors or may be the input and output reservoirs for 2D/3D fluidic circuits. The test pattern shown demonstrates both right angle and circular patterns in dry film photoresist (Dupont Riston 3030). The material has been layered prior to exposure to build up the thickness of the film and the features. This route of laminate construction followed by simple electronic mask exposure is a direct method to create high aspect ratio Microsystems (HARM) without the complexity of many HARM process.

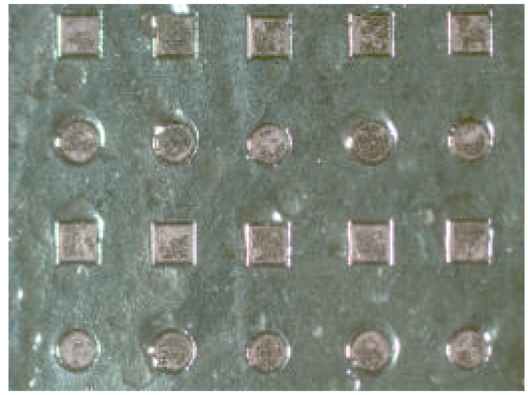

Figure 12: Microwells patterned on Nickel using the electronic mask lithography workstation

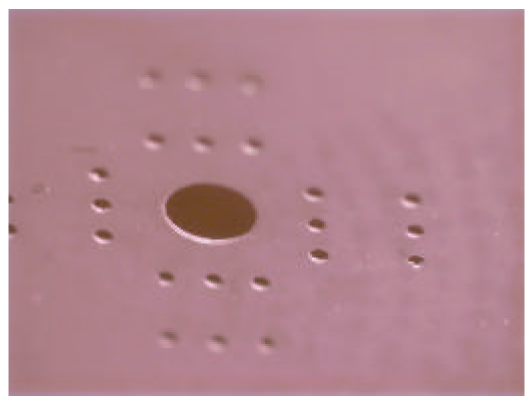

Figure 13: Plated thru holes/burst valves in double-sided Cu clad LCP material patterned with the SF-100 and etched with ferric chloride and KOH. Then plated with electroless Cu.

The process flow illustrated in figure 3 indicates a plated through hole as one of the elements possible within the PCBMEMS process flow. Also burst valves were mentioned above as models for rapid dimensioning, fabrication, and verification using the tool set. Figure 13 shows an example of a plated through-hole array in LCP/Cu of different pitch and different size diameter holes.

The final display of the breadth of the variable mask generating capability is through the use of the projected masks onto non-planar substrates. Traditional device architectures have been constrained by use of strictly planar substrates and thus have collapsed the degrees of freedom of designs substantially. Another design option is the use cylinders and spheres for the base substrate to impart channels onto. These non-planar devices may be actuators or microprobes with integrated fluid flow delivery, for example in medical devices. Figure 14 illustrates an example of a cylindrical rod patterned with Novalac type resist. The pattern has been written entirely around the rod piece. The pattern was written in three radial segments and the use of multiple variable masks permitted ease of alignment for the three segments in both the circumferential direction and along the length of the screw thread.

Figure 14: Rod photopatterned completely around using three mask projections around the circumference of the rod.

CONCLUSIONS

Microchannels are not limited to fluids alone. Small scale channels can be used to direct the flow of a variety of particles (ions. electrons, photons, fluid parcels). Mask free patterning of these microchannels offers distinct advantages over traditional photolithography methods. The most advantageous of these is the ability to expose patterns immediately upon design completion. In addition, the ability to write directly onto curved surfaces opens up multiple design possibilities not approachable using standard planar substrates and lithographic methods.

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NOMENCLATURE

q_m =mass-based flow rate
N_1 =Engineering unit conversion factor
C_d =orifice discharge coefficient
P =differential pressure across the orifice
Y =Expansion Factor (=1 for water)
d =orifice bore diameter
ρ =gas density
β =Ratio bore diameter to meter channel diameter D

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