SYMPOSIUM Q

Rapid Prototyping Technologies–Tissue Engineering to Conformal Electronics

November 28 – 30, 2001

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* Invited paper

SESSION Q1: DIRECT WRITING ELECTRONIC COMPONENTS
Chair: Douglas B. Chrisey
Wednesday Morning, November 28, 2001
Room 308 (Hynes)

8:30 AM *Q1.1
ISSUES IN MATERIALS SYSTEMS FOR DIRECT-WRITE PROCESSES. Kenneth H. Church, Sciperio, Inc., Stillwater, OK.

Materials systems for direct-write deposition by through-nozzle and quill-pen dispensing are presently the subjects of intense R&D efforts. Issues include viscosity, solids loading, agglomeration, solvent-system volatility, surface-energy interactions, and thermal-processing considerations. These parameters are related to the overall qualities of the dispensed lines as they pertain to geometries, dispensing rates, thicknesses, depositions of multiple pastes, substrate surface character, and depositions onto conformal surfaces. Exemplary results of fine-line-geometry deposition trials for two systems are presented.

9:00 AM Q1.2
LASER DIRECT WRITING OF PASSIVE MESOSCOPIC CIRCUIT ELEMENTS AND DEVICES FOR RF AND MICROWAVE APPLICATIONS. H.D. Wu, SFA Inc., Largo, MD; R. Modi, The George Washington University, Dept. of Mechanical and Aerospace Engineering, Washington, DC; R.C.Y. Auyeung, Naval Research Laboratory, Washington, DC; J.E. Vollmers, University of Virginia, Dept. of Physics, Charlottesville, VA; D.B. Chrisey, Naval Research Laboratory, Washington, DC.

A novel laser based transfer technique called Matrix Assisted Pulsed Laser Evaporation-Direct Write (MAPLE-DW) has been used to prototype various passive mesoscopic circuit elements and devices on Kapton substrate. With this technique, we have made circuit elements such as microstrip lines, resistors, capacitors, and inductors as well as devices such as integrated LC bandpass filters and RC band reject filters for RF and microwave applications. These components and devices were fabricated in air and at room temperature with subsequent thermal processing in furnace or selective laser sintering. The performance of these components and devices was characterized from 1 MHz up to 20 GHz using an impedance analyzer and microwave probe and/or a network analyzer and an universal text fixture. The results clearly indicate MAPLE-DW is a rapid prototyping and agile manufacturing approach that simplifies the processing and provides greater flexibility than is possible with screen printing approach.

9:15 AM Q1.3
NOVEL MICROSTAMPING METHODS FOR 3D CIRCUIT PATTERNING ON POLYMERS. Peter M. Moran, Institute of Materials Research and Engineering, SINGAPORE; William T. Chen, ASE (US) Inc., Santa Clara, CA.

We have developed a new microstamping method for patterning three-dimensional circuitry on polymer substrates. In this method a stamp is immersed in a colloidal suspension of polymer-stabilized palladium nanoparticles. The nanoparticles adsorb weakly to the stamps surface. A polymer substrate is then molded against the stamp and conforms to the stamps surface. The nanoparticles bond with the molded polymer and are transferred during separation. These particles act as a catalyst for subsequent electroless plating. This method is entirely additive and allows the formation of fine-line, buried and three-dimensional circuitry on polymers. In a previous study[1] we developed another microstamping method to produce freestanding bipolymer features. The bipolymer features produced were as small as 2 microns by 2 microns in cross-section and 10 microns tall and are potentially useful in applications such as nerve-guides and chemosensors. Possibilities of combining this method with our current nanoparticle stamping method to fabricate high aspect ratio metallized features will be discussed. (1) P.M. Moran and C. Robert, Appl. Phys. Lett., in press.

10:00 AM *Q1.4
RAPID RESPONSE COMPUTER AIDED MANUFACTURE OF PRINTED WIRING BOARDS. Gregory A. Jablonski, Paul H. Kydd, Parelec Inc., Rocky Hill, NJ.

Digital printing of conductive traces on conventional laminate and polymer film circuit substrates can provide circuits on demand in quantities of one to a few hundred, easily and inexpensively. This paper describes a computer-automated alternative to the conventional plate-and-etch technology for producing printed wiring boards. The process is based on newly developed metallo-organic decomposition chemistry for the direct, additive metallization of holes and printing of circuit traces. The new technology, named Parmod (r), has been used to prepare demonstration circuits with pure copper conductors and through hole metallization on laminate substrates, which are believed to be the equivalent of conventional plate-and-etch circuits. A description of the process is given and the results of testing the circuits produced are summarized. Parmod (r) Very Low Temperature thick film inks can be applied by screen-printing, electrostatic printing, ink jet printing, or by using a computer-controlled dispenser. The printed inks can be rapidly cured, in as little as one minute in conventional solder reflow equipment, making them attractive for use in rapid response systems. Further, their relatively low cure temperatures as compared to conventional thick film inks make it possible to use substrates that are common to the printed circuit board industry. New developments extending this technology to oxides as well as metals, permitting the printing of passive components as well as conductor traces are described.

10:30 AM *Q1.5
RAPID PROTOTYPING OF PLASTIC MICRO DEVICES BY EXCIMER LASER ABLATION. Thomas Klotzbuecher, Torsten Braune, Manfred Lacher, Institut fuer Mikrotechnik Mainz GmbH, Mainz, GERMANY.

Nowadays the application of micro devices in many fields like e.g. in the life sciences, chemistry and also optics strongly grows in importance. Micro structures often allow efficient processes with low resource consumption and the possibility of high integration. Typical examples are micro and nano titer plates for chemical screening or DNA chips for sequencing, micro mixers and reaction systems for synthesis on demand or micro optical elements like couplers for optical data transmission. Especially plastics are well suited for the cost effective large number fabrication, using high precision mould inserts with injection moulding or hot embossing. Since the micro devices become more and more complex (keywords: lab on a chip and micro total analysis systems) the fabrication of mould inserts will be more expensive and time consuming. This is the reason why often methods of rapid prototyping are required for design qualification and functionality test purposes during the development. It will be demonstrated that Excimer laser ablation is a well suited method for rapid prototyping of quasi-three-dimensional micro structures. Almost all polymers can be ablated by the UV laser radiation with very high accuracy, using mask projection techniques. Therefore, the choice of a suited polymer with adapted material properties like for e.g. chemical resistance, optical surface quality or bio-compatibility allows to account for the requirements of the corresponding application. Moreover, the prototypes can easily be transformed into mould inserts for large number fabrication, using the Laser-LIGA technique. The corresponding technologies will be explained and demonstrated with the aid of several examples, especially taking into account the material aspects.

11:00 AM Q1.6
LASER-BASED DIRECT WRITING OF ELECTRONIC COMPONENTS. B.H. King, M. Renn, M. Essien, P. Seigal, Optomec, Inc., Albuquerque, NM.

The microelectronics industry has been steadily shrinking feature sizes to around 0.1 microns. However, a corresponding pace has not been maintained in packaging, increasingly limiting the performance of electronic products. The packaging area for passive components such as resistors, capacitors, hi-gain antennae and batteries can be reduced by directly writing them onto the substrate. Further, by directly writing interconnects between passive devices solder joints may be eliminated, making the entire package more robust. Optomec is developing a laser-based technology for directly writing passive electronic components onto circuit boards and other substrates. The process has been demonstrated for interconnect metals, resistor and dielectric compositions and battery materials on substrates ranging from FR-4 to silicon. This process may find broad applications in the electronic packaging industry from products such as cell phones to component manufacturing. Recent results, including micron-scale deposition techniques, material developments, laser treatments of metals and dielectrics and component performance, will be presented.

11:15 AM *Q1.7
AN INTEGRATED TOOL FOR RAPID PROTOTYPING OF ELECTRONIC CIRCUITS USING A LASER DIRECT WRITE TECHNIQUE. Scott Mathews, Michael Duignan, Potomac Photonics, Inc., Lanham, MD; Paolina Atanassova, Hugh Denham, Superior MicroPowders, LLC, Albuquerque, NM; Alberto Pique, Rohit Modi, Ray Auyeung, Naval Research Laboratory, Washington, DC.

A laser based tool has been developed for the fabrication of electronic circuits. The tool integrates three separate functions on a single platform. These functions are deposition, laser processing, and laser micromachining. Deposition is accomplished by dispersing a target material in a thin layer over a transparent backing layer, holding the target material in close proximity to a receiving substrate, and irradiating the target material from behind with a short pulse UV laser. The UV pulse vaporizes a small amount of material at the target material/backing layer interface, thereby propelling the remainder of the target material toward the receiving substrate. Patterning is achieved either by translating the receiving substrate, scanning the laser beam, or a combination of the two. After transfer, most materials require some thermal processing; either oven baking or laser sintering. Fabricated circuits have included conductors (Ag, AgPd, AgPt, Cu), resistors (cermet and polymer thick film), and dielectrics(ceramic and polymer thick film). These materials have been patterned with feature sizes as small as 10 um and linear write speeds as high as 1 meter per second. The tool includes an integrated, near IR laser which can be operated both CW and pulsed for thermal processing. Laser sintering of metals, cermet resistors, and ceramic dielectrics has been demonstrated on low temperature, polymer substrates. The localized heating achievable with the laser allows the sintering or annealing of high temperature materials without damaging the underlying substrate. The tool includes a complete, state-of-the-art laser micromachining system, capable of milling recesses, drilling vias, trimming components, and excising circuits. No mask or phototools are required. No photoresists or wet chemistries are needed. The tool does not require a clean room environment. The combined functionality and speed result in a flexible and powerful tool for rapid prototyping of circuits, and potentially, small scale production.

11:45 AM Q1.8

MAPLE DIRECT WRITING OF PASSIVE ELECTRONIC MATERIALS FOR LOW TEMPERATURE CONFORMAL DEVICES. D.B. Chrisey, R. Modi, H.D. Wu, R.C.Y. Auyeung, H.D. Young, B.R. Ringiesen, and A. Pique, Naval Research Laboratory, Washington, DC; H. Denham, Superior Micropowders, Albuquerque, NM; and M. Duignan, Potomac Photonics, Lanham, MD.

We have utilized MAPLE DW (Matrix Assisted Pulsed Laser Evaporation Direct Write) to rapidly (~1 m/sec) deposit mesoscopic patterns (0.050 - 10 mm) of passive electronic materials and laser sintered them at low temperatures (<300°C) for applications in conformal devices. This technique is a novel CAD/CAM laser forward-directed transfer technique that utilizes a composite ribbon made up of powders, chemical precursors, and various rheological and surfactant materials to transfer to a polymer substrate in ambient air and at room temperature. We have characterized the mechanism and kinematics of the technique with high-speed imaging. The materials deposited included metals, high and low k dielectrics, polymer and cermet resistors, and ferrites. We have also deposited devices ranging in complexity from simple circuits and complete subsystems. The electronic properties of the materials were comparable to conventional thick film techniques such as screen printing, but this approach allows for rapid design changes, allows the deposition of multiple materials, and occurs at processing temperatures enabling more useful substrates. This presentation will outline the status of MAPLE DW of passive electronic materials and describe the future applications of the technique to other material systems.

SESSION Q2: RAPID PROTOTYPING SENSORS AND STRUCTURES

Chair: Stephen C. Danforth
Wednesday Afternoon, November 28, 2001
Room 308 (Hynes)

1:30 PM *Q2.1

STEREOLITHOGRAPHIC PROCESSING OF CERAMIC/ ORGANIC COMPOSITES FOR ORTHOPAEDICS. Jim H. Lee, Robert K. Prudhomme, and Ilhan A. Aksay, Department of Chemical Engineering and Princeton Materials Institute, Princeton University, Princeton, NJ.

ABSTRACT NOT AVAILABLECeramic stereolithography (CSL) is used to fabricate complex-shaped ceramic/organic composites by laser photocuring a concentrated ceramic dispersion in photocuring solutions layer-by-layer. The main processing parameters in CSL such as layer thickness, resolution, hatch spacing, and overcure depend on the knowledge of light propagation in concentrated multiple scattering dispersion. By incorporating biocompatible polymers as the matrix phase, biomaterials with controlled microstructure may be constructed.
Alumina (Al_2O_3) was used as the reinforcing phase in a matrix of 2,2-*bis(4-(2-hydroxy-3-methacryloxypropoxy)phenyl)* propane (Bis-GMA), a commonly used monomer in dental fillings. Free radical polymerization was initiated with *2-benzyl-2-N,N-dimethylamino-1-(4-morpholinophenyl)-1-butanone* (DBMP).
In studies dealing with the processing of these reinforced biocomposites, we investigated the depth of curing for model resin systems as a function of photoinitiator concentration. An optimal photoinitiator concentration that maximized the gel cure depth was observed. We probe this relationship through the development of a model that incorporates photoreaction kinetics, coupled with concepts of critical gel formation. The outcome is a model that complements the standard equation of stereolithography. We make use of the model in extending our work to nanocomposite fabrication, again using alumina.

2:00 PM Q2.2

RAPID PROTOTYPING OF CERAMIC BASED PHOTONIC BANDGAP STRUCTURES. Jennifer Synowczynski, Bonnie Gersten, Brad Klotz, Weapons and Materials Research Directorate, Army Research Laboratory, Aberdeen Proving Grounds, MD.

An inverted photonic band gap (PBG) structure was constructed from 3D CAD models that were printed as a polymer matrix using a precision rapid prototyper. The PBG structure that was constructed consisted of alternating layers of two 2D photonic bandgap structures. The first layer contained periodic arrangements of rods in air and the second layer contained a periodic arrangement of holes in a dielectric. The polymer matrix was then used as a mold to cast a slurry containing $BaSrTiO_3$/MgO ceramic powders and binders dispersed in ethanol. The mold was then removed to leave behind a ceramic green body that subsequently was sintered in air at high temperatures (1450 degrees C)to fully densify the part. Scanning electron microscopy was used to characterize the precision of the part. This study evaluates the effect of casting process, binder removal and shrinkage during sintering on the final net shape.

2:15 PM Q2.3

IMPROVEMENT OF SURFACE FINISH OF PARTS PRODUCED BY FUSED DEPOSITION OF CERAMICS (FDC). M. Bohlin, B. McEnerney, A. Safari, and S.C. Danforth, Rutgers University, Dept. of Ceramic and Materials Engineering; K. Seyed and M. Jafari, Rutgers University, Dept. of Industrial Engineering.

Fused Deposition of Ceramics (FDC) is a solid freeform fabrication process utilizing thermoplastic binders impregnated with ceramic powders. In this work, the ECG9 binder system and lead zirconate titanate (PZT) were used. One of the current limitations of the FDC process is that as-built surface finishes are not yet sufficient. Currently, the surface finish of as-built parts varies from 10 - 30 micrometers. Therefore, two surface processing methods were investigated to determine if green machining could produce sufficiently fine surface finishes. The first machining process examined was a post-deposition step, while the second process was machining during the build process. With the introduction of a green machining process prior to the binder removal and sintering steps, the average surface roughness, Ra, was reduced to approximately 1 micrometer. In order to accomplish the best surface finish, it was found that three key parameters needed to be controlled: work piece temperature, work piece feed rate and tool rotational speed.

2:30 PM *Q2.4

SLURRY-BASED 3DP AND FINE CERAMIC COMPONENTS. Michael J. Cima, Richard Holman, Emanuel Sachs, Dept. of MS&E, Massachusetts Institute of Technology, Cambridge MA.

The slurry-based 3DPTM is a solid freeform fabrication technique developed at MIT for production of fine ceramic components with complex geometries and fired densities in excess of 99% of theoretical density. Current research involves identification of the factors controlling minimum feature size in S-3DPTM. A balance between spreading of the binder solution on the surface of the S-3DPTM powder bed and infiltration was found to control minimum feature width, while interactions between the polymeric binder and the powder surface (polymer adsorption) control the minimum feature cross section. Droplet-on-demand printing of the binder solution has been introduced to improve resolution, decreasing the minimum feature width from 300 microns to less than 150 microns.

3:30 PM Q2.5

PROCESSING AND CHARACTERIZATION OF Al_2O_3 SKELETONS AND Al_2O_3/Cu ALLOY COMPOSITES. R.C. McCuiston, D.E. Niesz, and S.C. Danforth, Department of Ceramic and Materials Engineering, Rutgers University, Piscataway, NJ.

Fused deposition of ceramics (FDC) has been used to fabricate macroscopically graded ceramic skeletons. These Al_2O_3 skeletons were subjected to binder removal and sintering treatments. The sintered skeletons were then infiltrated with copper alloys. Both the skeletons and composites were characterized for micro and macro structure using optical and electron microscopy. Fracture toughness and hardness were determined using Vickers indentation. The authors will discuss potential applications for the macroscopically graded ceramic/metal composites, focusing primarily on impact.

3:45 PM *Q2.6
CREATION OF 3D MICRO-OBJECTS BY LASER CHEMICAL DIRECT-WRITE: PROCESSING AND APPLICATIONS. Michael Stuke, Kurt Mueller, Kirk Williams, Max-Planck-Institut f. biophys. Chemie, Dept. Laser Chemical Processing, Goettingen, GERMANY; Matthias Hagedorn, Torsten Mueller, Guenter Fuhr, Humboldt Univ, Berlin, GERMANY.

Three-dimensional aluminum oxide ceramic microstructures are laser-written by computer control from gas phase precursor mixtures of dimethylethylaminealane (CH3)2C2H5NAlH3 and oxygen O2, and partially metallized by aluminum Al or platinum Pt. In this way complex microelectrode systems are created suitable for precise trapping and touch-free handling of small charged and neutral objects. This talk will focus on applications with special emphasis on the touch-free catching, kicking and storage transfer of neutral particles in solution, including cells. Movie sequences will be shown to demonstrate this in realtime.

4:15 PM Q2.7
LASER FORWARD TRANSFER OF METALS, POLYMERS AND ORGANIC MATERIALS FOR DIRECT WRITE OF SENSOR DEVICES. Alberto Piqué, David W. Weir, Peter K. Wu, R. Andrew McGill, Bhanu Pratap, Craig B. Arnold, Ray C.Y. Auyeung, Brad R. Ringeisen, Richard A. Kant and Douglas B. Chrisey, Naval Research Laboratory, Washington, DC.

The use of direct write techniques for the rapid prototyping of sensor devices allows for the quick development of miniature, lightweight, embedded sensor systems for next generation commercial and defense applications. Using a laser forward transfer technique, we have demonstrated the ability to rapidly prototype temperature, pressure, chemical and biological sensor devices on almost any type of surface. Various types of miniature sensor designs, including sensor arrays have been fabricated using metals, polymers, composites and organic materials under ambient conditions. The laser forward transfer process is computer controlled which allows the sensor design to be easily modified and adapted to any specific application. Furthermore, the same process enables the fabrication of complete sensor systems by incorporating the passive electronic components required for sensor readout. Examples of various types of sensors and their performance, together with current and future applications where these types of sensors might play a role will be provided.

4:30 PM Q2.8
APPLICATION OF STEREOLITHOGRAPHY TO MINIATURE GAS SENSING SYSTEM WITH POROUS SILICON SENSORS. Laam Angela Tse, Lenward Seals, James Gole, David Rosen and Peter J. Hesketh, Georgia Inst of Tech, Atlanta, GA.

Stereolithography offers the capacity to fabricate microstructures with aspect ratios greater than 100 at lower cost and with shorter fabrication times than a micromachining process[1]. The benefit of integrating the stereolithography with a micro-fabricated component is that it can improve the 2.5 dimensional structures obtained from a micro-machining process to 3 dimensional structures. A gas chromatography column has been fabricated on silicon to demonstrate the capability of stereolithography technology combined with micro-fabrication processes for designing and fabricating of a miniaturized chemical gas sensing system. Stereolithograpy also allows the integration of all the fluidics components into the microfluidics system in the presence of leak free packaging[2]. A miniaturized gas chromatographic column (0.5 and 1 mm ID) with a length of 100 cm has been fabricated with a stereolithography machine (SLA 3500, 3D Systems, Valencia, CA) from liquid photopolymer SL 7510 (3D Systems). Since the dimensions of a column fabricated with SLA can be changed easily in a CAD design, the length and dimensions of the column can be designed differently for different applications. Fabrication of a gas chromatographic column in 3 dimensions is a good illustration of the use of stereolithography as, instead of fabricating the entire length of the column on the same plane, it can be fabricated on multiple planes, stacking all the layers together to minimize the overall size of the device. To apply the micro-column to an application in chemical detection, a silicon micromachined chemical sensor can be integrated into the micro GC column for chemical gas sensing. Since the micro-columns are made of transparent polymer, the gas can be detected using an optical method[3]. The miniaturized gas chromatographic column system can correspond to the integration of polymer micro-columns with a chemical sensor, valves, and pump corresponding to a functional device that can be constructed with stereolithography technology. References [1]P. Jacob, "Stereolithography and other RP&M Technologies", Society of Manufacturing Engineers, 1996. [2]K. Ikuta, T. Hasegawa, T. Adachi, and S. Maruo, "Fluid Drive Chips Containing Multiple Pumps and Switching Valves for Biochemical IC Family", Proceedings of the IEEE Conference on MEMS, 2000, pp. 739-744. [3]K. Ikuta, S. Maruo, T. Fujisawa, and A. Yamada, "Micro Concentrator with Opto-Sense Micro Reactor for Biomedical IC Chip Family", Proceedings of the IEEE Conference on MEMS, 1999, pp. 376-381.

SESSION Q3: ENERGY STORAGE AND MODELING
Chair: Michael J. Stuke
Thursday Morning, November 29, 2001
Room 308 (Hynes)

8:30 AM *Q3.1
DIRECT WRITE MICROBATTERIES FOR NEXT-GENERATION MICROELECTRONIC DEVICES. Karen E. Swider-Lyons, Alberto Pique, Craig Arnold, Ryan Wartena, Naval Research Laboratory, Washington, DC.

The next generation of miniature electronic devices will require lightweight, high power energy sources. We are using the matrix-assisted pulsed-laser evaporation process, MAPLE DW, to write power sources directly into microelectronic devices. A range of battery designs and arrays are rapidly fabricated from commercially available materials at low temperatures and ambient pressure. The power source design is easily modified with this CAD/CAM process for optimum performance in specific devices. Conformal application of the power sources facilitates space and weight conservation in the microelectronics. Examples are given for planar pseudocapacitors and stacked alkaline batteries.

9:00 AM Q3.2
EFFECTS OF LASER PROCESSING ON MATERIALS USED FOR DIRECT WRITE MICROBATTERIES. Craig B. Arnold, Alberto Pique, Karen E. Swider-Lyons, Naval Research Laboratory, Washington, DC.

We are examining the influence of laser energy and wavelength on the electronic and chemical properties of microbattery systems. Li- and Zn- based microbatteries are produced by a novel laser forward transfer process called matrix assisted pulsed laser evaporation direct write(MAPLE-DW) which can produce structures on the mesoscopic (1 micron to 1 mm) length scale under ambient conditions and onto various types of substrates. Additional control over the interfacial and film structure is gained by subsequent laser processing. Using the UV transfer laser (lambda = 355 nm, 30 ns FWHM), we perform several in situ operations including surface processing, triming and micromachining of the transferred materials and substrate. Ex situ processing such as annealing, melting and selective laser sintering of the transferred materials are performed using an IR laser (lambda = 10.6 microns, ms to CW pulse width). Finally, we analyze these microbattery devices for their storage and discharge properties as a function of the above laser processing conditions on the deposited films.

9:15 AM Q3.3
EVALUATION OF DIRECT-WRITE CAPACITORS. Michael N. Nguyen, Robert L. Parkhill, Robert M. Taylor, and Kenneth H. Church, Sciperio, Inc., Stillwater, OK.

Capacitor components have been manufactured by direct-write hardware and methods. Their electronic properties and behaviors have been evaluated in terms of firing method, substrate material, and paste materials systems. Firing methods included conventional oven firing and laser processing. Deposition substrates included ceramics and Kapton plastic. Materials systems under evaluation included traditional screen-printable paste systems, polymer-based paste systems, and new low-decomposition-temperature paste systems. Physical properties under evaluation included temperature coefficient of capacitance, component variance, frequency response, and sensitivity to humidity.

10:00 AM Q3.4
DIRECT-WRITE PROCESSES AS ENABLING TOOLS FOR NOVEL ANTENNA DEVELOPMENT. Bryan S. Irwin, Robert M. Taylor, Kenneth H. Church, Sciperio, Inc., Stillwater, OK; James W. Culver, Raytheon Systems Company, St. Petersburg, FL; Douglas H. Werner, The Pennsylvania State University Department of Electrical Engineering, University Park, PA.

Significant research effort is regularly applied to the goal of reducing the size of radio-frequency antennas while maintaining all of the positive attributes of proven but relatively large antennas. Such parameters as frequency response (multiple or single), bandwidth, and complexity of the antenna-driver balun structures require iterative optimization. The direct-write processes now available have enabled the insertion of reactive-loading elements as integral parts of the antenna structure, especially new conformal designs. These reactive-loading elements were used in conjunction with fractal design techniques to achieve antenna devices that were reduced in size to as much as half that of traditional counterparts. The performances of miniaturized antennas constructed by direct-write methods were evaluated and compared to those of traditional antenna structures.

10:15 AM Q3.5
LASER-DIRECT WRITING OF CONDUCTOR AND DIELECTRIC MULTILAYERS FOR STORAGE CAPACITOR APPLICATIONS. D. Young, H.D. Wu, R. Modi, H. Denham, D.B. Chrisey, Naval Research Laboratory, Washington, DC.

In the past, laser-direct writing has been used successfully to write single layers of conductive, dielectric and resistive inks, which are then converted into functional materials by thermal or photothermal processing. Many ink-substrate and material conversion issues are easily addressed in these single-layer cases, because the substrates used for writing of electronics are typically smooth and chemically inert. However, the fabrication of capacitors, bridges for routing conductor lines and ferrite core inductors and all require multiple layers of patterned material. Direct-writing of these multilayer structures is much more challenging. In this paper, we present the successful direct writing of Ag/glass-ceramic/Ag parallel plate capacitors by laser-direct writing of Ag and dielectric inks. After conversion, the Ag layers exhibit <10 times bulk resistivity, and the dielectric layer has a dielectric constant of >150 and loss of $<2\%$. Using this example, multilayer issues such as material interdiffusion, reaction, precursor wicking and surface roughness will be discussed.

10:30 AM Q3.6
DIELECTRIC PROPERTIES OF PLASMA SPRAY DEPOSITED $Ba_{0.68}Sr_{0.32}TiO_3$. K. Ahn, B.W. Wessels, Northwestern Univ, Dept of Materials Science and Engineering, Evanston, IL; R. Greenlaw, S. Sampath, SUNY-Stony Brook, Dept of Materials Science and Engineering, Stony Brook, NY.

Plasma spraying is under investigation as a potential method for the deposition of materials for conformal electronics. In this study, the dielectric properties of high k dielectric $Ba_{0.68}Sr_{0.32}TiO_3$ (BST) thick films prepared by plasma spray were investigated. The frequency and temperature dependence of the dielectric properties were measured using an impedance analyzer. The relative dielectric constants of BST layers measured at room temperature were in the range of 100 $\sim$200 and were dependent upon the deposition parameters. The dielectric properties of BST layers showed Curie-Weiss behavior above room temperature. However the Curie temperature was suppressed for the compositions studied. After annealing at 500°C in air, the dielectric constant increased up to 460. This increase in dielectric constant was attributed to the crystallization of an amorphous second phase. Annealing effects on the microstructure were studied using transmission electron microscopy.

10:45 AM Q3.7
DIRECT WRITING OF FERROELECTRIC CAPACITORS AND THEIR IN SITU THERMAL PROCESSING USING A NOVEL LASER BASED TECHNIQUE. R. Modi, The George Washington University, Dept of Mechanical and Aerospace Engineering, Washington, DC; H.D. Wu, SFA, Inc., Largo, MD; R.C.Y. Auyeung, Naval Research Laboratory, Washington, DC; J.E. Vollmers, University of Virginia, Dept of Physics, Charlottesville, VA; D.B. Chrisey, Naval Research Laboratory, Washington, DC.

Ferroelectric capacitors have been fabricated using a novel laser based transfer technique called Matrix Assisted Pulsed Laser Evaporation-Direct Write (MAPLE-DW) with subsequent in situ thermal processing by selective laser sintering. MAPLE-DW is a versatile direct writing technique capable of writing a wide variety of materials on virtually any substrate in air at room temperature. Barium titanate (BTO) and lead magnesium niobate (PMN) based capacitors with capacitance to area ratio (C/A) of 72 nF/cm^2 and loss tangent of about 4% at 1 MHz were deposited on alumina and kapton substrates under ambient conditions. Electrical characteristics of these MAPLE-DW deposited capacitors were studied at a wide frequency range (1 MHz to 1.8 GHz).

11:00 AM Q3.8
MICROSTRUCTURAL STUDY AND THERMAL MODELING OF LASER FORMED Ti-6Al-4V. S.M. Kelly, S.L. Kampe, Virginia Tech, MS&E Department, Blacksburg, VA.

A two-dimensional thermal model for AeroMet Corporations Laser Additive Manufacturing (LAM) process has been developed to predict the thermal history of Laser Formed Ti-6Al-4V structural parts. The motivation behind the thermal model is to be able to predict time-temperature conditions responsible for certain microstructural features, which are observed in as-processed components. For example, the LAM Ti-6Al-4V microstructure exhibits large columnar prior-β grains that have grown through multiple deposited layers, a well-defined heat-affected zone in the substrate, and the presence of macroscopically-visible layer bands. The microstructure of the layer band consists of larger colonies of acicular α outlined in transformed β, whereas the adjacent material consists of smaller colonies having the same type of structure. In the current work, the thermal model is used to verify that the presence of layer bands is a result of a narrow region of material experiencing a short-duration thermal excursion into the β phase field from the α β phase field.

11:15 AM Q3.9
ULTRA HIGH-SPEED IMAGING OF A LASER FORWARD TRANSFER PROCESS USING A COLLOIDAL INK LAYER. D. Young, R.C.Y. Auyeung, H. Denham, A. Pique, D.B. Chrisey, Naval Research Laboratory, Washington, DC; D.D. Dlott, Department of Chemistry, University of Illinois, Urbana-Champaign, IL.

Recently, focused laser pulses have been used to desorb material from thin (10um) layers of colloidal inks, for pattern generation and rapid prototyping applications. The resolution and homogeneity of such written structures is strongly dependent on laser and material parameters. In this work, ultra high-speed (1ns time-gating) time resolved optical microscopy has been used to study the transfer dynamics in this process. A a-terpineol/barium titanate ink layer was irradiated with 355nm, 150 ns laser pulses at atmospheric pressure. Observable plume formation begins after the end of the laser pulse, and continues for >1 ms. The plume consists of micron-size particles and propagates both normally and parallel to the ink surface, at velocities that are strongly dependent on laser fluence. There is evidence of a supersonic transition at approximately 0.2 J/cm^2. It appears that the forward transfer mechanism can be either solvent vaporization or particle ablation in the colloidal layer. A discussion of the transfer mechanism and its relation to improved writing properties will be presented.

SESSION Q4: LIQUID AND DISPENSING DEPOSITION

Chair: Karen E. Swider-Lyons
Thursday Afternoon, November 29, 2001
Room 308 (Hynes)

1:30 PM *Q4.1
APPLICATIONS OF INK-JET PRINTING TO DIRECT WRITE TECHNOLOGIES. D.B. Wallace, P.W. Cooley, B.V. Antohe, Donald Hayes, MicroFab Technologies, Inc., Plano, TX.

This invited presentation will outline the advances that have been using ink-jet printing to direct write materials.

2:00 PM *Q4.2
INDUSTRIAL NEEDS FOR NEW DIRECT WRITE TECHNOLOGIES. Tim Ellis, Kulicke & Soffa Industries, Willow Grove, PA.

This presentation will summarize the industrial needs for new direct write technologies.

2:30 PM Q4.3
NEW TYPE OF POWDER MATERIAL FOR INK-JET PRINTING. Andreas Pfister, Rolf Mulhaupt, Freiburger Materialforschungszentrum, Freiburg, GERMANY.

3D Printing (3DP) of powder is a versatile solid free form fabrication technology for producing concept models in an office environment. This technology was developed by the MIT and is now commercialized by Z Corporation. In 3DP, a powder material is applied layer by layer on a flat surface and bonded together by means of a waterborne liquid binder, that is delivered by an inkjet printhead. The traditional used powder consists of an adhesive, that can be a sugar, a water-soluble polymer or plaster. Optionally these powders can contain also a filler or a fiber to provide structural reinforcement and dimensional stability to the final article. Powders that are actually available on the market are a mixture of dextrose/cellulose/starch (ZP11, Z Corporation) and a plaster based powder (Z100, Z Corporation). All these materials have the disadvantage, that the final article dissolves again getting in contact with water. Therefore these materials must be posttreated by wax or resin infiltration. We have now developed a new kind of powder material for 3DP, that produces articles which are water resistant and show enhanced mechanical strength (compressive strength). The final article can optionally be posttreated. Due to the white colour of the powder, it is also suitable for use in colour-printing. A very important factor for the mechanical strength of such powder based objects, is the porosity of the final article and the amount of welds between the powder grains. We used microtomography, to image 3D architectures with a resolution of $8\mu m$. This insight into 3D architectures is the key to optimization of new powder systems with improved property profiles.

3:15 PM Q4.4
DIRECT INK-JET PRINTING OF ALUMINA COMPONENTS.
Chris Ainsley, Nuno Reis and Brian Derby, Manchester Materials Science Centre, UMIST, Manchester, UNITED KINGDOM.

Alumina slurries containing up to 45% by volume ceramic particles suspended in paraffin waxes have been developed with viscosity sufficiently low to allow direct ink-jet printing. Components fabricated by printing have been dewaxed and sintered and any distortion introduced during these processes measured. Differences in shrinkage are correlated with the direction of droplet motion during printing and the influence of droplet impact on local microsegregation in the deposited body investigated prior to firing.

3:30 PM Q4.5
ANALYSIS OF DROP-ON-DEMAND INK-JET PRINTING FOR RAPID PROTOTYPING.
Dong-Youn Shin, Manchester Materials Science Centre, UMIST, Manchester, UNITED KINGDOM; Paul Grassia, Dept. of Chemical Engineering, UMIST, Manchester, UNITED KINGDOM; Brian Derby, Manchester Materials Science Centre, UMIST, Manchester, UNITED KINGDOM.

Ink-Jet printing technology has been one of the earliest technologies used for rapid prototyping. In order to print materials from highly loaded slurries it is necessary to understand the mechanics of drop formation in a drop-on-demand print head. Here we analyse the actuation mechanisms of a piezolelectric cylindrical actuator and the hydrodynamics of the fluid within the print head to achieve more realistic boundary conditions for the numerical simulation of the drop formation process. Linearised Navier-Stokes equations for Newtonian flow are solved for an axisymmetric piezoelectric actuator. These results are inserted into a numerical simulation using Flow-3D. The predicted results of the simulations are shown to agree well with experimental measurements.

3:45 PM Q4.6
SURFACE MODIFICATION AND SELECTIVE ELECTROLESS PLATING OF POLYIMIDE USING AN Nd-YAG LASER.
Z.L. Li, S.Z. Yow, H.M. Phillips, P.M. Moran, Institute of Materials Research and Engineering, SINGAPORE; Gang Zhao, Primanex Corporation, CA; W.T. Chen, ASE (US) Inc., CA.

Direct laser patterning on polymers is of great interest both for scientific understanding of laser-materials interactions and for potential application in rapid prototyping of conformal electronics. Pulsed Nd-YAG laser surface modification and subsequent selective activation and electroless plating have been investigated on polyimide films in air. It has been shown that fine-line circuitry can be obtained using this method. Laser irradiation on Kapton initially caused localized surface peeling that gradually formed individual corn structures. As laser light was continuously delivered to the surface the number of corns increased and eventually covered whole irradiated area. The surface structural evolution was studied by SEM and XPS analysis. After irradiation the sample was immersed in a colloidal suspension of Pd/PVP particles. Seeding occurred on the irradiated regions only. These regions were then metallized using electroless plating. We have used this method to plate selectively within microchannels. Our results show that plating ability of laser irradiated surface and the adhesion between plated metal and polyimide depend not only on the surface roughness, but also on the chemical composition of the surface. The surrounding atmosphere influences the chemical composition of the laser-irradiated surface. Surfaces became deactivated after few days in air or ten minutes in a UV ozone environment (100C). XPS and TOF-SIMS measurements were employed to understand this phenomenon.

4:00 PM Q4.7
CHEMICAL VAPOR DEPOSITION BY PULSED ULTRASONIC DIRECT INJECTION OF LIQUID PRECURSORS PRODUCES VERSATILE METHOD FOR CREATION OF THIN FILM CIRCUITS AND DEVICES.
Mark W. Leiby, Sono-Tek Corporation, Milton, NY.

Unique ultrasonic direct injection method allows novel use of nanophase materials, polymers, metal-organic and ceramic precursors. By use of in situ-forming and modification of process parameters, morphology and structure may be varied to produce desired characteristics. By sequential application of these strategies one may fabricate MEMS, OLED's, deposit conformal coatings, create surface acoustic wave (SAW) chemical sensors and many other thin film circuits and devices. Some of these will be demonstrated.

4:15 PM Q4.8
DIRECTED ASSEMBLY OF COLLOIDAL SILICA GELS.
G. Gratson, J. Smay, J.A. Lewis, University of Illinois, Dept of Materials Science and Engineering, Urbana, IL.

Mesoscale periodic structures were fabricated via robotic deposition of concentrated colloidal gels. During this directed assembly process, a colloidal "ink" ($\Phi \sim 0.5$) is extruded through a cylindrical nozzle (diameter ~10 to 1000 μm) to architect complex, 3-D structures in a layer-by-layer build sequence. We have studied the effects of colloidal stability, volume fraction, and particle size on flow behavior of such gels through a microfluidic (nozzle) element of varying size. Our aim is to develop a process map that elucidates the importance of gel rheology (e.g., τ_y and $P_y(\Phi)$), volume fraction, and nozzle/particle size ratio on this deposition process.

SESSION Q5: TISSUE ENGINEERING
Chair: Douglas B. Chrisey
Friday Morning, November 30, 2001
Room 308 (Hynes)

8:30 AM *Q5.1
CELL-BY-CELL CONSTRUCTION OF TISSUE BY LASER TRANSFER.
Bradley Ringeisen, Douglas Chrisey, Alberto Pique, Ray Auyeung, Barry Spargo, Naval Research Laboratory, Washington, DC; Peter Wu, Southern Oregon University, Dept of Physics.

In order to fabricate and interface biological systems for next generation applications such as biosensors, protein recognition microarrays, and engineered tissues, it is imperative to have a method of accurately and rapidly depositing different active biomaterials in patterns or layered structures. Ideally, the biomaterial structures would also be compatible with many different substrates including technologically relevant platforms such as electronic circuits, microfluidic devices, or even living tissue. We have developed a novel laser-based technique, termed matrix assisted pulsed laser evaporation direct write (MAPLE DW), that is able to direct write patterns and three-dimensional structures of numerous biologically active species ranging from solutions of proteins and antibodies to living cells. Specifically, we have shown that MAPLE DW is capable of forming mesoscopic patterns of living prokaryotic cells (E. coli bacteria), living mammalian cells (Chinese hamster ovaries, mouse pluripotent cells), and active proteins and antibodies (biotinylated bovine serum albumin, antiBSA). We find that our approach is unique in that it enables immobilized engineered tissues to be constructed cell-by-cell, depositing both the living elements and semi-rigid scaffolding required to build complex three-dimensional tissue structures. We will present experimental results on our recent efforts to fabricate tissue-based microfluidic networks as well as human osteoblast (bone)/chondrocyte (cartilage) cellular structures for hip and knee reconstruction.

9:00 AM Q5.2
AEROSOL-BASED DIRECT-WRITE OF BIOLOGICAL MATERIALS FOR BIOMEDICAL APPLICATIONS.
Gregory J. Marquez, Michael J. Renn, W. Doyle Miller, Optomec, Inc., Albuquerque, NM.

Applying life sciences and engineering principles to the study of cells and engineered tissue has resulted in various successes. These endeavors are poised towards development of functional neo-organs used as native tissue substitutes. Concurrent with this goal, technologies are directed in the general areas of biocompatible polymer scaffolds, biomimmetic extracellular matrices, control of stem cell differentiation, biomolecule signaling, and directed material delivery. Optomec Inc. is developing an aerosol-based direct write process for deposition of biological materials into three dimensional, micron-scale patterns. The process uses pneumatic atomization to produce aerosol droplets of proteinacious colloidal dispersions and whole cell suspensions. The droplets are entrained in an air stream and deposited with a proprietary deposition tool. The biological materials can be seeded into three dimensional polymer scaffolds and various substrate surfaces. Optomecs direct write process has applicability to the additive fabrication of engineered tissue. Other applications of the direct write tool include rapid prototyping of analytical biosensors, hybrid BioMEMS, and microarray devices.

9:15 AM Q5.3
DEVELOPMENT OF A SOLID FREEFORM FABRICATION METHOD FOR CONSTRUCTING FUNCTIONALLY TAILORED TISSUE REGENERATION DEVICES.
Suman Das, Dept. of Mechanical Engineering; Scott J. Hollister, Dept. of Biomedical Engineering; Paul H. Krebsbach, School of Dentistry, University of Michigan, Ann Arbor, MI.

This paper discusses the development of a new solid freeform fabrication method for constructing biomedical devices with designed compositions of materials specifically for the purpose of therapies related to tissue regeneration and controlled delivery of drug and bioactive factors. Selective laser sintering (SLS) is the proposed method to be used to build functionally tailored composite devices. Presently, commercially available SLS machines are only capable of constructing freeform objects using monolithic powder compositions. In this paper, we show concepts of a variant of SLS that will be capable of constructing objects with multiple materials and true three-dimensional heterogeneous composition. This capability of building functionally graded structures using multiple materials presents unique applications for regenerating multiple tissues. For example, a whole joint structure including a bone scaffold, combined with a cartilage scaffold and a ligament scaffold that have different functional architectures could be built in a single assemblage. We present results from preliminary experiments aimed at demonstrating capability of fabricating tissue regeneration scaffolds with discrete and graded polymer-polymer and polymer-ceramic interfaces. The polymers investigated include Polylactic acid (PLA), Polyglycolic acid (PGA) or their co-polymers (PLGA) while ceramics investigated include Hydroxyapatite (HA) and Tri-Calcium Phosphate (TCP).

10:00 AM Q5.4

MICROPATTERNED CELL ARRAYS FABRICATED BY COMBINING TEMPERATURE-RESPONSIVE POLYMER GRAFTING AND LOCALIZED LASER ABLATION.

Masayuki Yamato, Chie Konno, Yuki Isoi, Tatsuya Shimizu, Akihiko Kikuchi, and Teruo Okano, Tokyo Women's Med Univ, Inst Adv Biomed Eng Sci, Tokyo, JAPAN.

Most methods reported for cell-surface patterning are generally based on photolithography and use of silicon or glass substrates with processing analogous to semiconductor manufacturing. Here, we report a novel method to prepare patterned plastic surfaces to achieve cell arrays by combining homogeneous polymer-grafting by electron beam irradiation and localized laser ablation of the grafted polymer. Poly(N-isopropylacrylamide) was covalently grafted to surfaces of tissue culture-grade polystyrene (TCPS) dishes. Subsequent ultraviolet (UV) ArF excimer laser exposure to limited square areas (sides of 30 to 100 μm) produced patterned ablative photodecomposition of only the surface region ($\approx$100 nm depth). Three-dimensional surface profiles showed that these ablated surfaces were as smooth and flat as the original TCPS surfaces. TOF-SIMS analysis revealed that the ablated domains exposed basal polystyrene and were surrounded with PIPAAm-grafted chemistry. Prior to cell seeding, fibronectin was adsorbed selectively onto ablated domains at 20°C, a condition where the non-ablated grafted PIPAAm matrix remains hydrated and non-adhesive. Hepatocytes seeded at 20°C specifically adhered onto the ablated domains adsorbed with fibronectin. A one hundred-cell domain array was achieved by this method. This surface modification technique can be utilized for fabrication of cell-based biosensors as well as tissue engineered constructs.

10:15 AM Q5.5

DIRECT-WRITE CONSTRUCTION OF TISSUE-SCAFFOLDING STRUCTURES. Anatoly M. Kachurin and Kenneth H. Church, Sciperio, Inc., Stillwater, OK.

Direct-write hardware and methods traditionally used to deposit electronic materials are now being used to deposit tissue-scaffolding materials. Direct-write processes allow the rapid prototyping and construction of two- and three-dimensional structures potentially superior to those of the current state of the art. Modifications to typical tissue-scaffolding materials required for simultaneous compatibility with in vivo use and direct-write processes were investigated.

10:30 AM Q5.6

RAPID PROTOTYPING OF HYDROGEL SCAFFOLDS FOR USE IN TISSUE ENGINEERING. R. Landers, R. Mulhaupt, Freiburger Materialforschungszentrum, Freiburg, GERMANY; U. Huebner, R. Schmelzeisen, Universitaetsklinik für Mund-, Kiefer- und Gesichtschirurgie, Freiburg, GERMANY.

Tissue engineering is a very rapid developing area of science. The main focus has been on the culture of cells for the last ten years. Now, also the generation of individual 3D structures becomes important. A versatile 3D plotting technology has been developed at the Freiburg Materials Research Center in 1999 to produce scaffolds for tissue engineering applications with an interconnecting pore structure and an individual shape. This process is based on 3D dispensing of liquids into a viscous medium with a density similar to the plotting material. The resulting buoyancy force compensates the gravity force and therefore it is possible to dispense not only high viscous, but also low-viscous solutions without deformations. The contact between the plotting material and the medium causes solidification of the plotting material. One possibility to solidify the plotting material is a change in temperature. Therefore scaffolds have been designed from thermoplastic polymers (PLGA, PCl) or thermoreversible hydrogels (agar). Furthermore chemical reactions like complex formation have been used to generate hydrogel scaffolds under cell compatible conditions. Hydrogel scaffolds itself are suspected to play an important role in tissue engineering in future, because of their unique possibilities. They are biocompatible, enable diffusion of hydrophilic substrates, are flexible and closely connected to the extracellular matrix. No other Rapid Prototyping technique has been able to create biocompatible hydrogel scaffolds under cell compatible conditions up to now. The materials used in this new technique range from gelatine, collagen to polyelectrolyte complexes and fibrin. The growth of cells onto the surface has been demonstrated for different cell types. Furthermore the incorporation of living cells into the hydrogel during processing is demonstrated. This development in the RP field enhances the fabrication of living implants and is of interest for drug release.