Additive Manufacturing/3D Printing Focus Topic
Room: 211B - Session AM+EM+MS+TF-WeM

Materials, Designs, and Applications of Additive Manufacturing
Moderator: Erik B. Svedberg, The National Academies

8:00am **AM+EM+MS+TF-WeM1 An Overview of Additive Manufacturing**, ***Ed Morris**, R. Gorham*, NCDMM **INVITED**

"An Overview of Additive Manufacturing" - Additive manufacturing, also called 3D printing, has captured worldwide attention. Many believe that it is introducing the next industrial revolution because of its impact on product innovation and its unique manufacturing capabilities. America Makes – National Additive Manufacturing Innovation Institute is the first Manufacturing Innovation Institute established as part of a National Network for Manufacturing Innovation. Mr. Ed Morris, Director of America Makes and Vice President, National Center for Defense Manufacturing and Machining, will give an overview of additive manufacturing, and will discuss America Makes' actions to accelerate the use of additive manufacturing technologies in the United States and increase our nation's global manufacturing competitiveness.

8:40am **AM+EM+MS+TF-WeM3 Material Considerations and Opportunities for Laser Powder Bed Additive Manufacturing**, ***Michael W. Peretti**, D.H. Abbott*, General Electric Aviation **INVITED**

Additive Manufacturing (AM) has the potential to be a significant supply chain disruptor over traditional means for manufacturing a broad range of components for aerospace and other demanding applications. The ability to unlock complex, high-performance designs while reducing part count and number of manufacturing steps is beginning to revolutionize the way we think about making things. One of the key areas of development to further expansion of opportunities for AM is the production and supply of high-quality raw materials. This presentation discusses the critical issues for AM input raw materials, with particular emphasis on metal powder input stock for laser powder bed AM processes. Some background and experience from GE Aviation's development of the LEAP fuel nozzle will be shared, along with comments on the direction that the AM industry could take and the role of and potential for AM-specific metal powder alloys.

9:20am **AM+EM+MS+TF-WeM5 High Quality and High Speed EBM 3D Printing by the Integration of High Performance Electron Sources**, ***Colin Ribton***, TWI Ltd., UK, *S. del Pozo*, TWI Ltd. and Brunel University, UK

Production of high integrity components must use smart manufacturing methods to be efficient in use of scarce materials and other resources, and must ensure its environmental impact is minimized. Advanced manufacturing techniques, such as metal powder bed 3D printing , can be carried out by selective laser melting (SLM) or electron beam melting (EBM). In both cases the component is built layer by layer, with a beam as an intense energy source drawing each layer by melting powder. EBM is significantly faster than SLM and has been used to create metal parts in large quantities over the past 5 years. EBM machines have produced many tens of thousands of orthopedic implants. There are a number of key benefits in employing this manufacturing technology – including 'complexity for free', efficient use of material and flexibility of design. Increasingly, the aerospace industry is investigating the use of EBM for the manufacture of aircraft components and aero engine parts. However, the size of many of these components presents challenges to the EBM process in production rate and quality consistency over long build times (i.e. 150 hours).

The aim of this work is to overcome key obstacles concerning future requirements for EBM 3D printing for production of aerospace parts through the integration of two enabling technologies. The work will develop and integrate a novel plasma cathode electron source with an EBM machine focusing on realizing the enhanced capabilities of low maintenance, consistent manufacturing performance and higher productivity. Also, development and integration of an array probe device will provide quantified quality assurance of machine manufacturing readiness. The key research challenges will be the design of the electron source and optics and the development of new build procedures making best use of the new source.

The equipment will enable the wider adoption of EBM leading to efficient use of materials – particularly strategic titanium alloys and nickel based super alloys at first.

9:40am **AM+EM+MS+TF-WeM6 Laser Induced Forward Transfer of High-Viscosity, Polymer-Based VO_2 Inks**, ***Eric Breckenfeld**, H. Kim, T. Sutto, N. Charipar, A. Piqué*, Naval Research Laboratory

Additive manufacturing direct-write processes such as direct-write assembly, micropen, inkjet, and laser-induced forward transfer (LIFT) have become increasingly popular as interest in printable electronics and maskless patterning has grown. Compared to conventional lithography, these additive manufacturing processes are inexpensive, environmentally friendly, and well suited for rapid prototyping and large-area applications. At the same time, researchers have pursued various chemical solution deposition processes for combining additive manufacturing technology with functional electronic materials. Among a multitude of transition-metal oxides, vanadium dioxide (VO_2) has emerged as a material of particular interest due to its sharp semiconductor-to-metal phase transition near room temperature. A set of distinct optical and electronic properties which arise as a result of this transition have made VO_2 popular for thermochromic coatings, resistive switching, optical storage, light modulators, and other applications. Here, we demonstrate the development of a polymer-based solution for the deposition of VO_2 thin films. By exploring a variety of sintering and annealing conditions as well as exploring different polar solvents, we have optimized the growth of these films on glass and crystalline substrates. We go on to explore printing of VO_2 devices via the LIFT technique, which is notable for its ability to print high-viscosity inks and pastes. Finally, we will discuss our efforts toward the development of low temperature laser sintering in order to realize VO_2 films on substrates incompatible with high furnace temperatures.

11:40am **AM+EM+MS+TF-WeM12 Printing Multi-Functionality using Additive Manufacturing**, ***Ryan Wicker***, University of Texas at El Paso **INVITED**

Since the commercial introduction of Additive Manufacturing (AM) technologies more than two decades ago, considerable advancements in processing speed, accuracy, resolution and capacity have been achieved and the available AM materials have expanded considerably, enabling customized end-use products to be directly manufactured for a wide range of applications. Many AM technologies have been released that use different processes for fabricating the individual layers from a variety of liquid, solid, and powder-based materials ranging from photoreactive polymers to metals. In 2000, the University of Texas at El Paso identified AM as an emerging technology and invested strategically in establishing the W.M. Keck Center for 3D Innovation (Keck Center). The Keck Center has grown to occupy over 13,000 sq. feet with more than 50 commercial and experimental AM machines, representing 10 system manufacturers, nine distinct layer processing methods, and several custom AM-based patented and patent-pending systems. One particular focus of Keck Center research is on developing the methods and systems required to have automated control over material placement and structure creation, leading to, for example, the realization of complex 3D devices that integrate electronics and thus intelligence within mechanical structures as well as 3D spatially complex bioactive, implantable, tissue engineered constructs. There are myriad issues associated with combining multiple materials to create functional products – from the deposition and processing of different materials to the combined performance of the materials in the resulting product. Despite these issues, the opportunities for AM in aerospace, defense, biomedical, energy and enumerable other applications continue to expand as the achievable length scales in AM decrease, the number of materials available for use in AM increases, the performance of these materials are characterized and controlled in the final product, and new strategies for integrating AM with other manufacturing technologies are successfully demonstrated.

MEMS and NEMS
Room: 211A - Session MN+AM-WeM

Emerging Materials & Fabrication Technologies toward Scalable & Additive Nanomanufacturing I
Moderator: Philip Feng, Case Western Reserve University, Roya Maboudian, University of California at Berkeley

8:00am **MN+AM-WeM1 The Why, the What and the How of Nanomanufacturing**, ***Khershed Cooper***, National Science Foundation (NSF) **INVITED**

In 2010, at the conclusion of the review of the NNI, PCAST recommended greater emphasis on commercialization by doubling investment of the Federal Government in nanomanufacturing R&D. Federal agencies responded in various ways. The NNI Signature Initiative: Sustainable Nanomanufacturing was announced, OSD's MURI topic call included nanomanufacturing as a high-priority theme, and NSF announced the Scalable Nanomanufacturing solicitation. The private sector also responded to the need for nanotechnology commercialization through interest groups such as the NanoBusiness Alliance and, as the Institutes for Manufacturing Innovation multiply, nanoscience and nanotechnology appear to play an increasing important role. This is the 'why' of nanomanufacturing. Nanomanufacturing is the fabrication of nano-scale building-blocks, their assembly into higher-order structures and the integration of these into larger scale systems such that both heterogeneity and complexity are achievable with manipulation and control at the nano-scale. R&D activities address the nanomanufacturing value chain and manufacturability challenges such as scale-up and cost. This is the 'what' of nanomanufacturing. This talk will discuss these aspects of nanomanufacturing and 'how' the nanomanufacturing programs (NM, SNM, NSEC, NERC, SBIR) at NSF are meeting these challenges through support of basic and applied research involving novel ideas. Proposed ideas encompass a wide range of materials, processes and applications and are usually based on strong fundamental foundations. Research outputs are nanomanufacturing fundamentals that will help overcome barriers to large-scale, high quality production of nano-enabled products for the benefit of society.

8:40am **MN+AM-WeM3 Large-Area Nanoimprinting and Nanoplasmonics for Energy Harvesting, LEDs & Biosensing**, ***Stephen Y. Chou***, Princeton University **INVITED**

This talk will present (1) the technology advances and applications of nanoimprinting, a revolutionary nanofabrication method that not only allows the fabrication of nanostructures that could not be fabricated before, but also offers a viable way to mass manufacturing of nanostructures and hence commercialization; and (2) new nanoplasmonic structures for high efficiency solar cells and LEDs and ultrasensitive biosensing that have unprecedented properties and performances.

In nanoimprint, the presentation will address the advances in (a) planar as well as roll-to-roll nanoimprinting, (b) methods of making large nanostructure nanoimprint molds without using direct-write (e.g. electron-beam lithography), (c) self-perfection technologies, and applications in electronics, optics, optoelectronics, magnetics, biotechnologies, displays, and energy harvesting.

In nanoplasmonics, the presentation will discuss the advances in design large-area, high performance nanoplasmonics used for solar cell, LEDs and biosensing, in particular, two new nanoplasmonic structures: disk-coupled dots-on-pillar antenna-array (D2PA) and plasmonic cavity with subwavelength hole-arrays (PlaCSH). Significant enhances in energy efficiency and detection sensitivity have been achieved using D2PA and PlaCSH.

9:20am **MN+AM-WeM5 Scalable Nanomanufacturing of Plasmonic and Metasurfaces**, ***Regina Ragan***, *F. Capolino*, University of California Irvine **INVITED**

Nanodisks and nanoparticles serve as meta-molecule building blocks to tune plasmonic and metamaterial properties when arranged in planar and three-dimensional geometries. For example, the ability to control nanomaterial interfaces via colloidal synthesis allows for tuning of the plasmon resonance as well as mitigating losses affecting extinction spectra. In addition, colloidal assembly is beneficial as a high-throughput, wafer scale deposition method. We have achieved robust surface enhanced Raman scattering (SERS) sensors approaching single molecule detection limits *reproducibly* over large areas using colloidal assembly. Transmission electron microscopy data shows that by varying driving forces for assembly, diffusion versus electrophoresis, nanoparticle clusters with gaps between nanoparticles of 4 nm down to 1 nm, respectively, are obtained. Corresponding orders of magnitude decreases in detection limit allow for identification of fermentation products present in the parts per billion range in cystic fibrosis patients.

Arrays of tightly coupled metal and metal- dielectric nanoparticles also support narrow band resonances, Fano resonances, based on "dark" electric and/or magnetic resonances. We will discuss how material interfaces can be used to mitigate losses that eliminate Fano resonant features. For example, the extinction and absorption efficiencies resulting from an array of linear trimers of Au nanoshells in homogeneous environment show that efficiency is affected by changing dye concentration in nanoshells. The use of dyes as gain media induces sharpened Fano resonance features (attributed to the meta-molecule nature of the linear trimers) and increased maximum absorption efficiency at 422 THz. Using similar methods, circular nanoclusters (CNC) of metal nanoparticles can support a magnetic Fano resonance at 472 THzvia dipole moments forming a current loop underoblique TE-polarized plane wave incidence. In particular, array-induced resonances are narrower than single-CNC-induced ones and also provide even larger field enhancements, in particular generating a magnetic field enhancement of about 10-folds and an electric field enhancement of about 40-folds for a representative metasurface.Natural magnetism fades away at infrared and optical frequencies and artificial magnetism is cumbersome to achieve in these regimes, as conventional split ring resonators are difficult to scale down to optical wavelengths. Nanoparticles assembled from colloids are a scalable approach to engineer materials' electromagnetic properties.

11:00am **MN+AM-WeM10 Roll to Roll Processes at the University of Michigan: Continuous Patterning, Flexible OPVs, and Growth of Carbon Nanomaterials**, ***Jay Guo***, University of Michigan, Ann Arbor **INVITED**

Roll to roll fabrication is regarded as a high-throughput and cost-effective method for future manufacturing of flexible electronics, large area photonic elements and functional surfaces for a variety of applications. This talk will discuss a few examples of roll to roll processes developed at the University of Michigan. First, roll-based patterning processes will be introduced. These include roll to roll nanoimprint lithography (R2RNIL) based on mechanical deformation of polymers and capable of tens of nm resolution, photo-roller-lithography (PRL) by using flexible photomasks to pattern sub-micron and larger features continuously on a moving web. These techniques can be used in many applications, such as metal wire grid based transparent conductors. Next, fabrication of organic optoelectronics OLED and OPV by roll to roll coating processes such as blade coating, blade-slit coating will be discussed. The coating process should be selected properly by considering the thickness requirement for each active layers in the devices. Finally I will report some progress made by the UM team in the Scalable NanoManufacturing program in the roll based continuous growth of carbon nanotubes and graphene.

11:40am **MN+AM-WeM12 Nanotube Templated Manufacturing of Hierarchically Structured High Throughput Fluid Filters**, ***Andrew Davis***, *R.C. Davis*, *R. Vanfleet*, Brigham Young University, *N. Morrill*, Precision Membranes

High throughput microfilters for use in water purification have been developed to address filtration challenges by dramatically decreasing flow resistance and filter size while improving filter strength, longevity, and affordability. The microfilters were fabricated out of a high strength carbon-nanotube composite material using a process for precise hierarchical patterning on both the micro and nano scales.

12:00pm **MN+AM-WeM13 Improved Vacuum Deposition of Small Patterned Features Using Precision Shadow Masks and a Novel Low Pressure Sputtering Source**, ***Rob Belan***, Kurt J. Lesker Company, *V. Heydemann*, Advantech U.S. Inc, *S. Armstrong*, Kurt J. Lesker Company, *T. Fisher*, *B. Brocato*, Advantech U.S. Inc

A novel, low pressure sputter source has been used in conjunction with a precision shadow mask to deposit crisp features on glass substrates. The low pressure sputter source (LPSS) exhibits high-rate omnidirectional deposition and can form crisp lined features that are typically 5 µm to 50 µm in size when combined with precision mask technology. These feature sizes are a factor of 5x smaller compared to traditional magnetron sputtering at typical sputtering pressures (~1 Pa). The LPSS operates at pressures lower than 0.1 Pa which increases the mean free path of the sputtered atoms and reduces the spread of the deposited pattern through a shadow mask that is often associated with magnetron sputtering at normal pressures.

The LPSS sputters at rates (up to 3 Å/s) with precise rate control in the range of 1 Å/s to 3 Å/s for target/substrate distances from 76 mm to 101 mm. The first generation LPSS utilized a 137 mm x 5.4 mm aluminum cathode. The second generation LPSS employed a 826 mm x 32.5 mm high purity (10 ppm) aluminum cathode demonstrating the scalability of this novel deposition source.

Patterned thin films with thicknesses between 300 Å to 2,000 Å were deposited using the first and second generation low pressure sputter sources. The impact of ambient pressure, power and source/substrate distance on the resulting thin film was investigated. The deposition runs were conducted under static conditions, with stationary source and substrate, as well as with a scanning source.

Patterned features were deposited on display-grade borosilicate glass substrates by placing custom manufactured nickel shadow masks with apertures in the 20 µm to 50 µm size range between the low pressure sputter source and the substrates. The shadow masks are manufactured by an electroforming process that allows precise control of the mask thickness. Typical shadow mask materials are nickel and invar (FeNi36). As well as studying the sputtering process parameters of the LPSS the quality of the deposited patterned features were investigated using a variety of mask thicknesses and aperture dimensions.

The low pressure operation of the LPSS source enables thin film deposition of precision nanostructured patterns via shadow masks and sputtering, an area traditionally kept to evaporation methods. Results and conclusions of this work will be presented for this emerging fabrication technology.

MEMS and NEMS
Room: 211A - Session MN+AM-WeA

Emerging Materials & Fabrication Technologies toward Scalable & Additive Nanomanufacturing II
Moderator: Susan Burkett, The University of Alabama, Philip Feng, Case Western Reserve University

2:20pm **MN+AM-WeA1 Scalable Laser-Assisted Three Dimensional Printing of Nanomaterials**, ***Costas Grigoropoulos***, University of California at Berkeley **INVITED**

Nanomaterials and nanotechnology offer unique opportunities for fabricating devices of novel architecture and enhanced performance and can overcome system integration issues challenging current nanomanufacturing methods that are suited to planar geometries and are confined to top-down architectures. The central motivation of our work is to develop a new manufacturing method that offers scalability and flexibility enabling nanoscale device fabrication and integration in truly three-dimensional architectures over large areas and with arbitrary densities.

The core research strategy takes advantage of ultrafast laser beam processing for generating the scaffold multi-scale structures with 100 nm feature resolution. Two-photon polymerization is used to fabricate structures of tunable properties that are sensitive to pressure, light, heat and electrical stimulation. This technique, together with ultrafast laser micro/nanomachining will be adapted to multiple beam configurations in order to increase the processing throughput. Once the template is constructed, the directed self-assembly of block copolymers will be used to produce three-dimensional materials with tailored functionality where pattern amplification will be used to push the length scale to finer dimensions.

3:00pm **MN+AM-WeA3 Material Requirements and Challenges for NEM Logic Relays**, ***Tsu-Jae Liu***, University of California at Berkeley **INVITED**

The proliferation of mobile electronic devices and the emergence of applications such as wireless sensor networks and the Internet of Things have brought energy efficiency to the fore of challenges for future information-processing devices. The energy efficiency of a digital logic integrated circuit is fundamentally limited by non-zero transistor off-state leakage current. Mechanical switches have zero leakage current and potentially can overcome this fundamental limit. Contact adhesive force sets a lower limit for the switching energy of a mechanical switch, however, and also directly impacts its performance.

Stable operation with high endurance is a key requirement of switches for digital logic applications, and generally is a challenge for mechanical devices. The reliability of a miniature relay is limited not by structural fatigue or dielectric charging, but by contact oxidation or stiction.

This invited talk will begin with a review of recent progress toward the development of a reliable nano-electro-mechanical (NEM) relay technology for digital logic applications. It will then discuss the influence of contacting electrode material properties on relay performance and reliability. Opportunities for ultra-low-power computing with relays will be described.

4:20pm **MN+AM-WeA7 Microplasma-based Direct-write Patterning Processes for Additive Microfabrication**, ***Christian Zorman***, Case Western Reserve University **INVITED**

Metals comprise the most versatile and widely used class of materials in micro- and nanosystems, serving as electrical contacts, interconnects, electrodes, and even mechanical components. The most commonly used method to fabricate metallic structures involves physical vapor deposition combined with photolithography. This subtractive approach is effective in producing device structures with high pattern fidelity; however, such processes are limited by modest throughput, use of aggressive chemicals and high material wastage. Reliance on vacuum-based deposition processes limits process scalability and can hinder adoption in cost-sensitive applications. The emergence of flexible electronics has stimulated the development of additive approaches such as ink-jet printing for depositing patterned metal structures. Printing is attractive for such applications because it is performed under ambient conditions and can be integrated into large-scale roll-to-roll systems. However, the inks can be expensive and the variety of materials that are available as inks is limited. In addition, the organic capping agents that are used to stabilize nanoparticle-based inks are difficult to remove, which can compromise conductivity and mechanical integrity. Removal of the organics requires post-deposition processes that can limit the usage of certain polymer substrates. Adhesion of the printed structures to the substrates can also be a significant issue, especially in flexible applications.

This paper describes two novel microplasma-based processes under development at Case Western Reserve University to fabricate patterned metallic structures with micro- to nanoscale dimensions on rigid and flexible substrates. Our principal process utilizes electrons extracted from an atmospheric pressure microplasma to electrochemically reduce metal ions within a polymer substrate, selectively forming continuous metallic structures within that polymer. Recently, we have developed a microsputtering process that uses ions generated by an atmospheric-pressure microplasma. This process capitalizes on a physical vapor that is generated within a small capillary by Ar ion bombardment of small diameter metal wires. Forced Ar flow aids in the ejection of the resulting physical vapor through the orifice, which is positioned in close proximity to the substrate. Both processes are performed under ambient conditions thereby offering the same advantages as ink-jet printing, including potential scale-up to roll-to-roll processing. This presentation will detail the two processes and summarize most recent results in creating and characterizing micropatterned metal structures on a variety of substrates.

5:00pm **MN+AM-WeA9 Ni-induced Graphitization for Enhanced Long-term Stability of Ohmic Contact to Polycrystalline 3C-SiC**, *S. Chen, L.E. Luna*, University of California at Berkeley, *Z. You*, Tsinghua University, *C. Carraro*, ***Roya Maboudian***, University of California at Berkeley

Micro- and nano-electromechanical systems (M/NEMS) technology enables a diverse range of physical and chemical sensing under conditions close to ambient. However, there is a growing interest in sensors that can operate under harsh environments, including high temperature, high pressure, extreme radiation and corrosive. Sensing within these environments necessitates a robust semiconductor platform, different from those employed in traditional Si-based M/NEMS. A robust material, such as silicon carbide (SiC) provides compelling advantages not achievable with Si-based devices. SiC is a wide bandgap semiconductor with excellent mechanical, chemical and electrical stability, and thus is well suited for designing devices capable of operation in many harsh environments. Yet, harsh-environment stable metallization remains one of the key challenges with SiC technology. Here, we present a novel metallization scheme, utilizing solid-state graphitization of SiC, to improve the long-term reliability of Pt/Ti contacts to polycrystalline n-type SiC at high temperature. The metallization scheme includes an alumina protection layer and exhibits low stable contact resistivity even after long-term (500 hr) testing in air at 450 ºc. This study provides a feasible fabrication method and discusses the role of induced graphitic layer on contact stability.

5:20pm **MN+AM-WeA10 Fabrication of High Aspect Ratio Millimeter-Tall Free Standing Post Arrays using Carbon-Nanotube-Templated Microfabrication with a Sacrificial Hedge**, ***Guohai Chen***, *R. Vanfleet, R.C. Davis*, Brigham Young University

Carbon-nanotube-templated microfabrication (CNT-M) has shown precise high aspect ratio features in interconnected geometries.[1] However, the feature of isolated posts remains challenging.[2] Here we developed a process which involves fabrication of CNT posts connected by supporting hedges using CNT-M followed by oxygen plasma etching to remove the sacrificial hedges. We have explored the fabrication of posts with diameters from 10-40 um and heights up to 1.3 mm using sacrificial hedges of 1-5 um in width. With the CNT template, isolated free standing posts from a variety of materials can be made. For example, silicon or silicon nitride posts can be fabricated by infiltrated with silicon or silicon nitride. The creation of hybrid carbon/metal (copper, nickel) posts can also be realized through pulse electroplating.

1. J. Song, et al. Carbon-Nanotube-Templated Microfabrication of Porous Silicon-Carbon Materials with Application to Chemical Separations. Adv. Funct. Mater., 2011, 21, 1132.

2. K. Moulton, et al. Effect of iron catalyst thickness on vertically aligned carbon nanotube forest straightness for CNT-MEMS. J. Micromech. Microeng., 2012, 22, 055004.

Additive Manufacturing/3D Printing Focus Topic
Room: 211A - Session AM+EM+MS+TF-ThM

Technologies Enabled by Additive Manufacturing/Future of Additive Manufacturing
Moderator: Vincent Smentkowski, General Electric Global Research Center

8:40am **AM+EM+MS+TF-ThM3 Additive Manufacturing Enabling Advanced Technologies**, ***Teresa Clement***, Raytheon Company **INVITED**

The aerospace and defense industry for the last decade has taken note and contributed to significant advances in materials and process capabilities enabled by the field of additive manufacturing (AM) to fabricate beyond state-of-the-art advanced technologies. Conventional and non-conventional industry partners continue to push the boundaries of next-generation materials and multi-materials for additive manufacturing in order to further extend product capabilities. As these material developments continue evolving, our industrial base begins to realize the many benefits of AM: reducing lifecycle costs, engineering resilience and capability surprise by rapidly reconfigurable responses to adaptive adversarial threats, and the enabling of truly agile manufacturing via AM integration with the model based enterprise (aka marrying AM to the 'digital thread'). Some specific examples of advanced technologies are discussed herein, with examples of design iteration cycle-time reduction and use of material/process controls to verify by inspection and full characterization demonstrations of improved or unprecedented material performance and multi-functionality (electrical, thermal, structural, etc) made possible by additive manufacturing.

9:20am **AM+EM+MS+TF-ThM5 4D Printing: Three Dimensional Printing with Material Composition as the Fourth Dimension**, ***Douglas C. Hofmann***, NASA Jet Propulsion Laboratory, California Institute of Technology **INVITED**

Much of the current research in additive manufacturing in the aerospace community is focused on qualifying materials for service, which is a critical requirement for using additive materials. However, additive manufacturing is a powerful tool for creating materials and applications that cannot be replicated using traditional means. In the past, this has meant 3D printing complex geometries that cannot be easily machined. In the current talk, we will discuss what we call 4D printing; 3D printing where the fourth dimension is the material composition. By using multiple materials strategically in additive manufacturing, a whole new frontier of materials science becomes possible. The science behind these alloys and their applications will be discussed.

11:00am **AM+EM+MS+TF-ThM10 The Future of Additive Manufacturing and Multifunctional Parts**, ***Phill Dickens***, University of Nottingham, UK, United Kingdom of Great Britain and Northern Ireland **INVITED**

Additive Manufacturing has many advantages for producing complex components and systems and this has already started to be exploited for parts made of a single material. There is now much interest in the possibility of building parts with multiple materials so that electrical circuits and electronic items can be included within the structure. This paper will highlight some of the research that is taking place at the University of Nottingham and some recent examples of simple products that could exploit this technology.

Some of the issues will be covered where the layer manufacturing process provides some limitations.

Additive Manufacturing/3D Printing Focus Topic
Room: 211A - Session AM+EM+MS+TF-ThA

Additive Fabrication for Electronic Devices and Systems
Moderator: Jim Fitz-Gerald, University of Virginia, Gregory Whiting, Palo Alto Research Center

2:20pm **AM+EM+MS+TF-ThA1 Additive Printing for Flexible Electronic Devices**, *A.C. Pierre, **Ana Claudia Arias***, University of California at Berkeley **INVITED**

The area of printed electronics has been focused on the use of new classes of semiconducting and conducting materials in two main applications, displays and photovoltaics. Both applications require materials long-term stability, long shelf life as well the need for patterning and deposition over large areas. Over the past 10 years significant progress in the performance of printable materials has been reported including highly efficient solar cells, light emitting diodes and thin film transistors with mobilities as high as 10 cm^2/Vs. The work is highly motivated by the potential for high through put, high volume, low cost manufacturing. While large area electronics continues to be a good application for printed flexible devices, wearable medical devices, which benefit from new form factors, represent a good shift in direction of research in the field. Wearable medical sensors have the potential to play an essential role in the reduction of health care costs as they encourage healthy living by providing individuals feedback on personal vital signs and enable the facile implementation of both in-hospital and in-home professional health monitoring. In printed flexible electronics however, there are no standards for materials set, device models and fabrication methods. This lack of standards slows down design of new systems and the success of the technology as a whole. In this talk, I will review the state of the art of devices produced by printing and introduce a blade coating method that yields highly homogeneous flexible thin films that are applied to LEDS, photodiodes and TFTs. The application of these devices as building blocks for flexible electronics systems will also be discussed.

3:00pm **AM+EM+MS+TF-ThA3 Digital Microassembly for High-performance Printed Electronics**, ***Eugene Chow**, J.P. Lu, G.L. Whiting, D.K. Biegelsen, S. Raychaudhuri, A.R. Völkel, J. Veres, P. Maeda, I. Matei, S. Nelaturi, L.S. Crawford*, Palo Alto Research Center (PARC) **INVITED**

Digitally printing micro-scale pre-fabricated building blocks instead of simpler materials enables an alternative route to printed electronics and opens up fundamentally new manufacturing capabilities. However, existing printing technologies do not provide the required accuracy and orientation control to print such micro objects. We will describe a demonstration of the fundamental process steps of such an electronic chip printer based on electrographic manipulation and xerographic concepts.

4:00pm **AM+EM+MS+TF-ThA6 3D Printed Bionic Nanomaterials**, ***Michael McAlpine***, University of Minnesota **INVITED**

The ability to three-dimensionally interweave biology with nanomaterials could enable the creation of bionic devices possessing unique geometries, properties, and functionalities. The development of methods for interfacing high performance devices with biology could yield breakthroughs in regenerative medicine, smart prosthetics, and human-machine interfaces. Yet, most high quality inorganic materials: 1) are two dimensional, 2) are hard and brittle, and 3) require high crystallization temperatures for maximally efficient performance. These properties render the corresponding devices incompatible with biology, which is: 1) three dimensional, 2) soft, flexible, and stretchable, and 3) temperature sensitive. These dichotomies are solved by: 1) using 3D scanning and printing for hierarchical, interwoven, multiscale material and device architectures, 2) using nanotechnology as an enabling route for overcoming mechanical discrepancies while revealing new effects due to size scaling, and 3) separating the materials synthesis and 3D printed assembly steps to enable conformal integration of high quality materials with biology. The coupling of 3D printing, novel nanomaterial properties, and 'living' platforms may enable next-generation nano-bio interfaces and 3D printed bionic nanodevices.

Additive Manufacturing/3D Printing Focus Topic
Room: Hall 3 - Session AM-ThP

Additive Manufacturing/3D Printing Poster Session

AM-ThP1 Anisotropic Evaluation of Mechanical Properties Related to Printing Direction and Development of Nanocomposite Materials to Establish Direct Digital Manufacturing, ***Hiroaki Sakaguchi***, *A. Matsumuro, K. Takeda*, Aichi Institute of Technology, Japan

3D printing technique is strongly leading the next industrial revolution in all over fields. The manufacturing methods are used by additive processes using successive layers of a lot of kind of materials. In the past few years, the rapid development of 3D technologies has changed from data visualization models and so on to the manufacturing of industrial production including mass-production (DDM). Many difficult problems should be overcome in order to establish DDM technology as the general industrial products manufacture method. One of the representative problems is the durability or strength of the products. 3D printing systems deposits melt or soften materials in a layer state on solid parts. Layered structures are formed in the whole products, and extreme low strength interfaces are fabricated at the same time. It is necessary to optimize a printing direction according to the load that determines the strength and durability of the product as one of manufacturing process.

Our study investigated an optimal molding direction procedure with respect to mechanical properties. Tensile and three points bending tests were done for standard plate type specimen made of polymer (ABS-like, Strasys Co., Ltd) using Ink-Jet-Type 3D printer (Connex500). We made three types of specimens, which were varied in the printing direction, respectively. These experiments mean that the effect of directions of layers entering in the molds on important mechanical properties. Three type specimens for tensile direction were molded as follows: (S1) plane molding with printing layers parallel to tensile direction, (S2) plane molding with vertical layers to tensile direction and, (S3) vertical molding with vertical layers to tensile direction. Experimental results of tensile strength, Young's modulus and rupture stress of each specimen showed remarkable differences. The detail results were as follows: tensile strength of (S1) 50 MPa, (S2) 39 MPa, (S3) 35 MPa, Young's modulus of (S1) 1.1 GPa, (S2) 0.8 GPa, (S3) 0.7 GPa and rupture stress of (S1) 59 MPa, (S2) 46 MPa, (S3) 37 MPa. Bending test results showed the similar tendency of those of Young's modulus. These results became clear strongly significant specific anisotropy of mechanical properties related to printing directions. Therefore, establishment of DDM needs the logical molding process and construction of the database of mechanical properties of individual materials. Furthermore, another important problem concerning DDM must be development of new materials with strength enough for practical use. Now we have studied new nanocomposite materials with innovative high strength. We will present the results at the conference.

AM-ThP2 A New Technique to Make an Insulating AlN Thin Film to be Conductive by Spontaneous via Holes formed by MOCVD and its Application to realize Vertical UV LED on n^+Si Substrate, ***Noriko Kurose***, *Y. Aoyagi*, Ritsumeikan University, Japan

A new Technique to make an insulating AlN thin film to be conductive by spontaneous via holes formed by MOCVD and its application to realize vertical UV LED on n^+Si substrate

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Abstract

For growing AlGaN epitaxial layer on Si substrate, AlN buffer layer between Si substrate and AlGaN epitaxial layer is indispensable to avoid Si melt-back phenomena coming from direct contact of AlGaN to Si substrate. However, AlN is insulating material even though highly doped. To fabricate vertical type device like vertical UV LED and vertical UV light sensor, the conductive n-AlN is indispensable to insure direct current flow from p-electrode to n-Si substrate. We have succeeded in developing a new technique to grow conductive n-AlN using spontaneous via holes in AlN buffer epitaxial layer grown on n+Si substrate using MOCVD and succeeded in fabricating and operating vertical UV-LED and vertical UV sensor using this technique.

Via holes in AlN buffer layer are spontaneously formed by introducing thin Al layer deposition on the Si substrate. This Al thin layer forms a mask to make spontaneous via holes. Formation of via holes are confirmed by AFM and EDX measurement. Via holes are filled by conductive n-AlGaN and the current flows through these via holes. This current flow through via holes is confirmed by EBIC measurement. The density and the size of via holes are controlled by changing the growth condition of MOCVD. The size of via holes can be varied from 0.1 to 2μm depending on the TMA feeding amount in an initial stage of Al thin layer formation. By growing the p-n junction on the layer with multi quantum wells we have succeeded in vertical LED fabrication (substrate removal free vertical LED, RefV-LED) and operation with direct current flow from p electrode to n^+Si substrate at the wavelength of 350-400nm with good I-L and I-V performance and near field pattern. The built in voltage of the p-n junction was 3.8V and the break down voltage was more than 35V. The built in voltage is almost same as the band gap of AlGaN used in this RefV-LED. The large breakdown voltage of this device shows us that good p-n junction is formed. Our device can be fabricated without any photoresist processes and is simple to fabricate. These results show us our techniques will open a new window to fabricate a new DUV LED and UV sensor as well.

AM-ThP3 Novel Deep Si Etching Process for Green IOT, ***Takahide Murayama***, ULVAC Inc., Japan

TSV (Thru Silicon Via) application for 2.5D silicon interposers and 3D stacked devices is expected to realize a next-generation semiconductor device applied for upcoming IOT world with high packaging density, power saving, and high-speed signal transmission, etc. Generally, SF6 gas has been applied to form TSV in dry etching process because of its useful properties; reasonable cost, chemical safety, and dissociation property which generates a lot of fluorine radicals. Abundant fluorine radicals contribute to achieve higher silicon etching rate, but in the perspective of Global Warming Potential (GWP), SF6 has extremely high potential (GWP = 22200, 100 year base), gives a great impact to greenhouse effect. So, various gases have been offered to alternate SF6. In series SFx (x=0 to 6), there are limited species which have industrial stability, some of them characteristic properties in the points of low GWP and dissociation to generate fluorine radicals. SF4 gas has very low GWP in SFx series . Because SF4 immediately reacts with H2O in atmosphere, generates HF and SOx. GWP for HF and SOx have not been set due to their water-soluble property . In addition to low GWP property, the bond strength in SF4 has unique property. In SF6, SF5-F bond strength is 387 ± 13 kJ/mol. On the other hand, SF3-F bond strength in SF4 is 354 ± 13 kJ/mol . So, there is an expectation that SF4 can generate abundant fluorine radicals compared with SF6. From above properties, SF4 may be one of the SF6 alternative gases for TSV dry etching process.

AM-ThP4 High Resolution Two Photon and 3D Holographic Lithography Structure Production and Conversion to Higher Index Materials, ***Steven Kooi***, MIT Institute for Soldier Nanotechnologies

3D structured polymeric materials are produced by multi-beam laser interference or two photon direct write lithography[1] using either a 355 nm pulsed Nd:YAG laser or a 780 nm Ti:Sapphire femtosecond laser. Samples are also constructed by combining the two techniques.

In order to obtain more interesting and measurable optical properties, the polymeric structures produced by holographic lithography and two-photon lithography are converted into higher index of refraction materials (Si and Ge) by atomic layer deposition, reactive ion etching and chemical vapor deposition techniques.

Optical properties of the photonic structures produced are calculated and measured by local reflectivity and transmission measurements as well as with near field scanning optical microscopy. The 3D structure quality and all steps of the transformation from polymeric to high index materials are also characterized by serial focused ion beam (FIB) milling and imaging.

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