

MICROTECHNOLOGY-BASED ENERGY AND CHEMICAL SYSTEMS AND MULTI-SCALE FABRICATION

Brian K. Paul, M. Kevin Drost
Oregon State University, Corvallis, OR

ABSTRACT

Microtechnology-based Energy and Chemical Systems (MECS) are devices which process bulk amounts of fluids within networked configurations of thermal, mechanical and chemical unit operations each based on highly-parallel arrays of microchannels. These miniaturized energy and chemical systems enable large quantities of fluid to be processed in small amounts of space and, in Europe, the application of MECS technology is called process intensification. The use of microchannels results in shorter diffusional distances which permit shorter residence times in channels, shorter channel lengths and, consequently, more compact systems. All of this is accomplished with no pressure drop penalty. As a result, MECS devices have the potential to revolutionize the processing of mass and energy where a premium is placed on mobility, compactness, or point-of-use production. This paper reviews some of the underlying concepts that enable MECS technology, considers the impact of this technology on society, the means by which they are made and, as a consequence, considers the role of the manufacturing engineer.

Keywords: microtechnology, energy systems, chemical systems, process intensification, manufacturing engineer.

INTRODUCTION

Over the past 40 years, there has been a growing emphasis in manufacturing research on the fabrication of devices with multiple length scales. Multiple length scale systems, or simply multi-scale systems, are defined as systems with feature sizes in at least two different length scale regimes (i.e. macro, meso, micro, nano, etc.) for the improved physical or chemical system performance. Examples of multi-scale systems include integrated circuits, microelectromechanical systems (MEMS), and micro total analysis systems (μ TAS). For example, within microelectronics, nano-scale gates are embedded within micro-scale circuits that are connected to meso-scale bonding pads and ultimately macro-scale chip-scale packages (CSPs) and printed circuit boards (PCBs). Smaller gate sizes permit higher component densities improving both speed and cost. At the same time, meso-scale pads permit electrical interconnection while CSPs and PCBs simplify handling and foster component modularity.

One emerging class of multi-scale systems is Microtechnology-based Energy and Chemical Systems (MECS). MECS are highly-parallel microfluidic devices that rely on embedded nano and micro-scale features to improve heat and mass transfer. As shown in Table 1, the key distinguishing feature of MECS is that they use microchannels to process *bulk fluids*. By contrast IC's, MEMS and μ TAS devices are used in some fashion to generate or process *information* whether in signal acquisition, signal processing or knowledge acquisition. Most microfluidic applications (e.g. μ TAS) involve processing nanoliters or even picoliters of fluids for the purpose of conducting lab-on-a-chip type experiments and, ultimately, to extract *knowledge* or *information* from these experiments. However, MECS devices are used to process bulk amounts of *fluids* such as tanks full of gasoline (fuel reformers) or rooms full of air (distributed HVAC). Consequently, as processors of *mass* and *energy*, MECS devices are relatively large.

To process large quantities of fluids within microchannels, the microchannels must be arrayed. Therefore, most MECS devices typically involve the integration of one or more microchannel arrays, called unit operations (e.g. micromixer, microseparator, microreactor, microheat exchanger, etc.), into a microsystem. Examples of MECS unit operations include microchannel heat exchangers, which have demonstrated heat fluxes 3 to 5 times higher than that of conventional heat exchangers.^{1,2} Other examples include microreactors for waste remediation consisting of nanocrystalline catalysts embedded within the walls of a microchannel array connected to macro-scale fluidic connectors. Examples of application areas for MECS microsystems include advanced climate control³, fuel processing⁴, and microdialysis⁵ among others.

UNDERLYING CONCEPTS

MECS devices are primarily focused on taking advantage of the extremely high rates of heat and mass transfer available in microchannels to radically reduce the size of a wide range of energy, chemical and biological systems. Typically a MECS device will have dimensions on the order of 1 to 50 cm but it will include embedded, highly-parallel arrays of microchannels where individual channel dimensions are on the order of 100 μ m in height by

Table 1. A comparison of four different types of multi-scale systems.

Parameter	Integrated Circuits (ICs)	MEMS Devices	Micro Total Analysis Systems (μ TAS)	MECS Devices
Primary function of device	Information/signal processing	Mechanical actuation /information/signal processing	Analytical processing i.e. 'Lab on chip', 'Fluid in-Answer out'	Bulk fluid processing device-heat/mass transfer
Materials used	Semi-conductors & ceramics. Metals used for interconnects	Metals, Semi-conductors, polymers and ceramics	Metals, Semi-conductors, polymers and ceramics- Biocompatibility is a key issue	Mostly limited to metals and polymers due to high operating temperatures
Primary components of system	Transistors, switches	Mechanical device for motion, electronic device for signal processing	Fluid processing, electrical, mechanical and optical systems	Micro-channels for heat and mass transfer, surface reaction
Device Scale (Size of full device)	Dies range from few mm to few cm-square or rectangular dies	Sizes range from few mm to few cm	Few centimeters to few inches	Few mm to several hundred centimeters
Feature Scale (E.g.: transistor size in IC)	Highly microscopic: Features range from tens of nm to 0.25 microns	Microscopic: Few microns to several hundred microns	Multi-scale: Few microns to few mm	Multi-scale: μ channels are 20 to 250 microns; catalysts, nanocoatings and pores are submicron.
Device Tolerances	Alignment tolerances are in the nm ranges for high-end IC's	Several hundred nm range	Few microns to several hundred microns depending on size	Few microns to several hundred microns depending on size
Fabrication Methods	Lithography techniques (additive/subtractive), Silicon micromachining	Lithography, surface and bulk micromachining	Multiple modes of fabrication exist due to variety of components on system	Microlamination and limited micro-investment casting
Applications	Processors, memory cards, video cards, etc (general electronics)	Bubble jet print heads, micro-mirrors, airbag sensors, accelerometers, etc	Bio-MEMS, DNA and tissue analysis, gas chromatographs, etc	Fuel processors, microheaters, portable power generators, etc
Benefits	Small devices, Fast Processing-Can be integrated into other components	Fast response of mechanical devices coupled with information processing.	Enhanced portability, decreased analysis time, small sample volume	High rates of heat and mass transfer, portable, decentralized fluid processing

several mm in width. (A human hair has a diameter of approximately 80 μ m.) By taking advantage of the enhanced rates of heat and mass transfer in the embedded microchannels, researchers have typically been able to reduce the size of a variety of energy and chemical systems by a factor of 5 to 10.^{1,2,6,7}

How does this all work? Single-phase flow in a 100 μ m high channel will, in almost all cases of interest, be laminar, with Reynolds numbers typically between 1 and 100. In laminar flow, the residence time required to have the fluid reach thermal equilibrium with the walls of the channel decreases as D^2 where D is proportional to the height of the channel. If we decrease the channel height by a factor of 10, we will decrease the required residence time by a factor of 100. This means that, in theory, a heat exchanger with 100 μ m high channels would be 1/100th the size of a heat exchanger with 1 mm high channels for the same heat transfer rate and it can be shown that for laminar flow, the increased pressure drop associated with the smaller channels is exactly off set by the decreased length of the channel required to deliver the same heat transfer rates. In effect we get a theoretical factor of 100

reduction in size with no increase in pressure drop. Ultimately, by going to smaller channels we will reduce the diffusion barrier to the point where other processes such as axial conduction along the heat exchanger determine residence time for thermal equilibrium. At that point, further reductions in channel dimensions will not result in reduced residence time.

While single-phase flow in microchannels is well understood, processes that involve wall effects such as phase change and surface tension are significantly different in micro-scale geometries. Boiling is an example. The limited experimental investigations of boiling in microchannels suggest that the process of phase change in a microchannel is different from macro-scale devices. However, published performance for microchannel evaporators and condensers show a significant improvement in performance when compared to single phase microchannel devices, suggesting that as our understanding of phase change in microchannels improves we can expect a further improvement in the performance of microchannel heat exchangers.

Mass transfer is similar to heat transfer in microchannels. The residence time that reactants need to reach complete conversion in a catalytic gas phase reactor also decrease by D^2 if the residence time is dominated by diffusion rather than reaction kinetics. Many important reactions such as steam reforming are catalytic gas phase reactions where the primary barrier to short residence time is the time it takes for the reactant to diffuse to the catalyst site and for the products to diffuse back into the bulk flow. Reductions in residence time and reactor size on the order of 20 times have been reported in the literature.⁶ Ultimately, by going to smaller channels we will reduce the diffusion barrier to the point where reaction kinetics will determine residence time for complete chemical conversion. At that point, further reductions in channel dimensions will not result in reduced residence time.

TECHNOLOGICAL IMPACT

The advancements described above will allow the development of more compact energy and chemical microsystems that could significantly impact the way in which mass and energy are processed and consumed in society. Examples of current MECS microsystem developments at Oregon State University include man-portable heat pumps, on-board automotive fuel reformers for fuel cells, and dime-sized, wearable biosensors for detecting toxins. In the future, chemical microreactors for producing bleach or laundry detergent from more concentrated, benign feedstocks may be a standard feature on every washing machine usurping vertical supply chains for the production of household chemicals. These new technologies will have dramatic effects on the distribution of goods in industry as the processing of mass and energy becomes more decentralized.

Successful development of MECS technology will enable the development of a new class of miniaturized energy, chemical and biological systems. Examples of systems and products that can result from MECS include: compact cooling systems for electronics and aviation applications; distributed hydrogen production for automotive fuel cells; high energy density batteries for manportable power and micro-scale power applications; distributed, residential space conditioning; exhaust-driven automotive cooling; man-portable cooling; catalytic microreactors for waste cleanup; in-situ resource processing for space exploration; and CO₂ remediation and sequestration among others.

MULTI-SCALE FABRICATION

Much of the promise of MECS depends on the availability of economical methods of production that allow MECS to compete with the cost of existing centralized energy and chemical systems (e.g. HVAC). While MECS devices may include features with nano-scale or micro-scale dimensions, the development of the technology has emphasized materials and fabrication techniques that are significantly different from conventional silicon-based micromachining. MECS devices are implemented mostly in metals, ceramics and selected polymers due to a need for thermal and chemical properties in applications ranging from man-portable heat pumps and automotive fuel reforming. In contrast, most of information processing miniaturization technologies such as IC, MEMS and μ TAS devices are based on semiconductors.

In particular, microlamination architectures have been offered as one approach to the economical production of MECS devices.⁸ As shown in Figure 1, microlamination involves the patterning, registration and bonding of thin layers of material, called laminae, to produce monolithic microsystem devices with embedded, high-aspect-ratio microchannel arrays. The production of energy and chemical systems with microlamination schemes reduces the issue of energy and chemical system implementation from centralized plant construction to discrete part manufacturing which is the domain of the manufacturing engineer. Therefore, one outcome of the trend toward

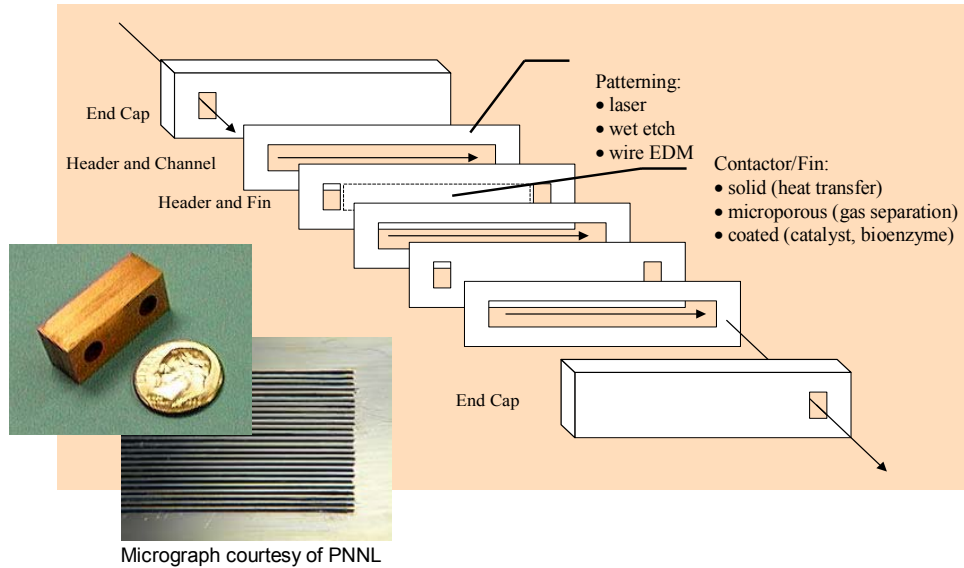


Figure 1. Conceptual presentation of a microlamination architecture.

energy and chemical systems miniaturization will be a growing dependence of the chemical and energy industries on the manufacturing engineering discipline.

Although microlamination architectures are currently the basis for producing commercial products, very little is known about the cost and technology drivers involved. To date, most MECS work has been performed in the prototyping and laboratory environment. As a result, a focus of future manufacturing research efforts will be to study the economics of microlamination. Also, it is proposed that more research is needed to understand the mechanisms of warpage and dimensional stability within microlaminated devices. These and other issues related with MECS production are the domain of the manufacturing engineer.

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