Development of An Integrated Silicon Micro Methanol Steam Reformer to Understand Thermal Management Issues in Micro Fuel Processor

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The processing of high density liquid hydrocarbon fuels appears to be the most promising method of supplying a hydrogen stream for feeding portable fuel cells. Liquid hydrocarbons could quickly become a viable energy source for portable power if an efficient, lightweight, and portable fuel processor/fuel cell integrated system were made available. Because of size and portability, microreactor technology has shown promising results in the field of fuel processing to convert hydrocarbon fuels to hydrogen, for the production of electricity [1,2]. Microreaction can facilitate highly compact power sources through integration of a fuel cell with all the unit operation components of a fuel processor along with microstructured sensors, actuators and other “balance of plant” devices.

Methanol (CH_3OH) is an attractive fuel for portable power, offering high hydrogen-carbon ratio, high energy density (5600 Wh/kg), and ready availability [3]. Moreover, methanol is sulfur free and can be reformed relatively easily at low temperatures (250-300ºC), simplifying the micro fuel processor design. Figure 1 shows a schematic for processing of methanol to produce hydrogen-rich gas suitable for a low temperature (70-80ºC) proton exchange membrane (PEM) fuel cell .

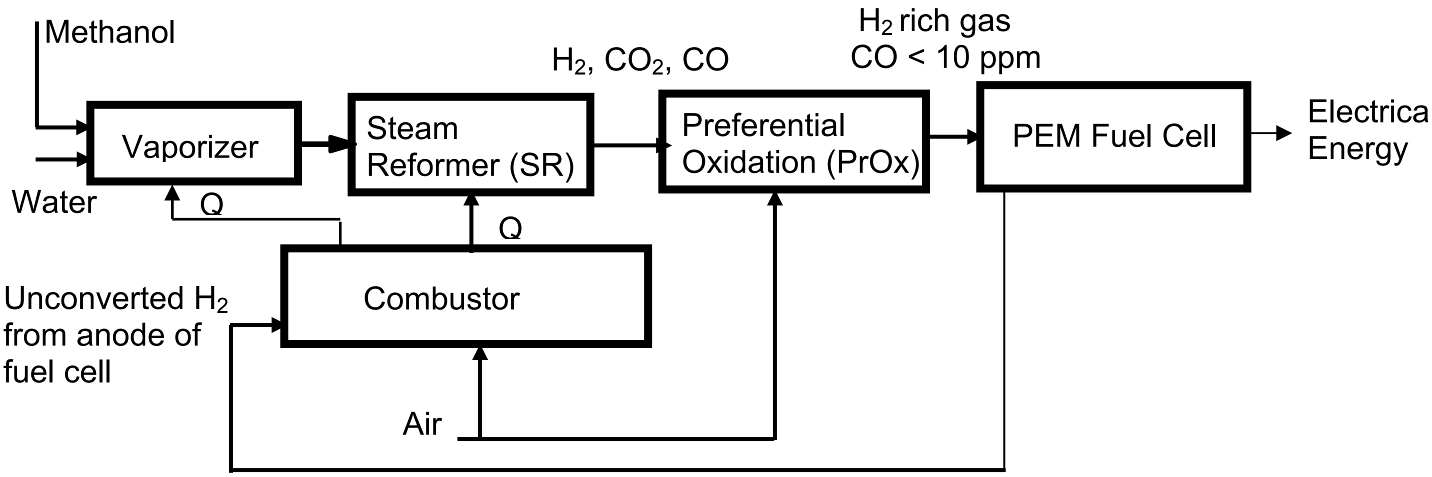


Figure 1. Processing steps required for generating high purity hydrogen from methanol

Considerable efforts are being made to develop an integrated fuel processor/fuel cell standalone system; however several universal challenges exist for the realization of practical micro fuel processors. Based on the literature and research conducted by our group, the following key issues are observed with fuel processing at small scale [4].

- Miniaturization of system components
- Heat management
- System complexity and packaging
- Kinetic evaluation for each unit operation
- Water management
- Miniature balance of plant components
- Internal energy demand
- Fate of exhaust gases
- Dynamic control

The need for miniaturization directs the use of microchemical systems in the field of fuel processing. The demand for a greater energy per volume and weight has naturally led to the investigation of microreactors which can take the form of any of the essential fuel processor elements including desulfurizer, steam reformer (SR), preferential oxidation (PrOx) reactor, etc.

We are exploring silicon microfabrication technology to achieve miniaturization. Silicon is lighter than stainless steel; it possesses high mechanical strength, chemical inertness, thermal stability, and large thermal conductivity. With the established silicon microfabrication technology, it is possible to create novel microchannel and reactor configurations in the sub-millimeter range with tight dimensional controls. An important advantage of silicon microfabrication is its compatibility with thin film technology. This facilitates eventual on-chip integration of functional elements like sensors and actuators allowing compact process control subsystems.

Thermal Integration Issues in Micro Fuel Processor

The management of heat in a compact format is perhaps the most crucial challenge for micro scale fuel processors. The fuel processor needs effective thermal coupling to allow transfer of energy from the heat producing combustor to the endothermic SR. Coupling endothermic and exothermic components of the fuel processor and minimizing losses can achieve high thermal efficiency. However, such coupling must be accomplished in a manner that permits the maintenance of specific temperatures in the various components as shown in Figure 2 and maintains the surface of the package near room temperature.

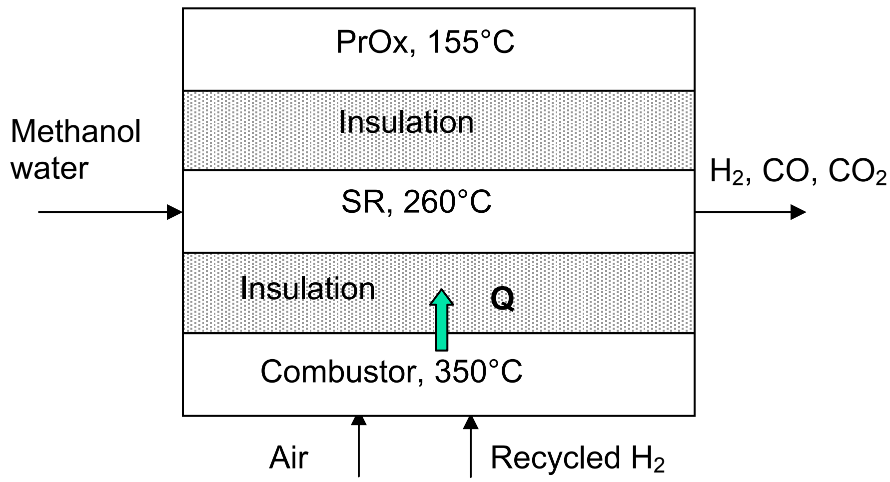


Figure 2. Integration of fuel processing components

The objective of this work is to demonstrate a silicon microreactor-based methanol reformer as a key fuel processing component with emphasis on thermal integration from a system perspective to achieve miniaturization and understand thermal integration issues. As shown in Figure 3, a silicon micro SR is designed and integrated with microfabricated insulation as dictated by overall system design. A thin-film microfabricated heater is used to simulate integration with a combustor by controlled heat introduction.

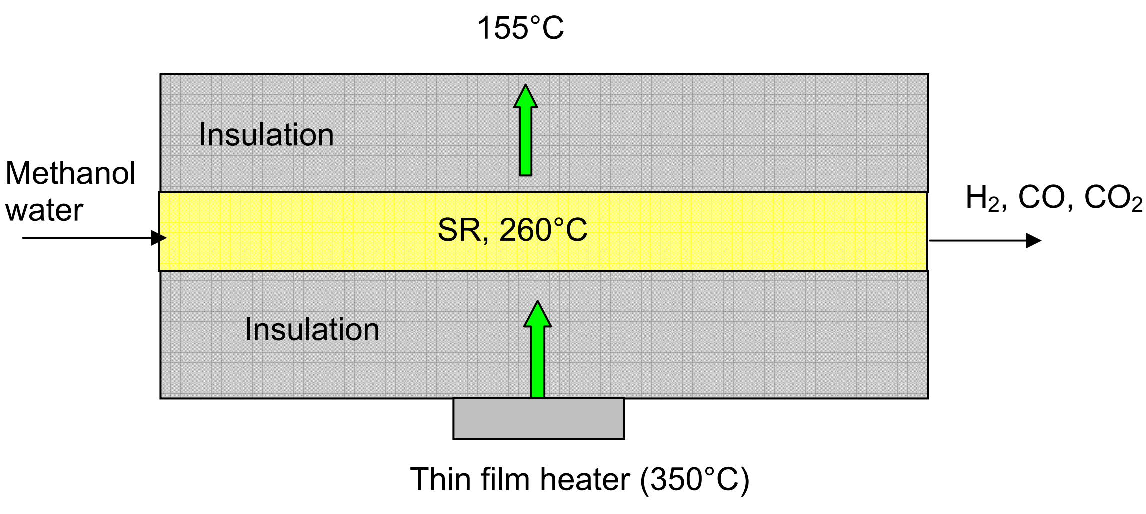


Figure 3. Demonstration of thermally integrated SR microreactor

Thermal Coupling and Insulation

Because of the short conduction paths inherent to microreactors, high performance insulators are needed between fuel processing components to isolate the high temperature components. The objective is to have insulating materials that can offer ultra low thermal conductivity to bridge these temperature differences and to minimize conductive and convective heat losses to the surroundings without adding much to the weight and volume of the total system.

The best commercial insulators have thermal conductivities in the range of 0.02 W/mK and are difficult to integrate into a microfabricated unit. However, vacuum packaging of microreactors can provide an effective means of insulation. From the kinetic theory of gases, it is known that the thermal conductivity of a gas is approximately independent of pressure for atmosphere and above, and decreases with sub-atmospheric pressures. A microfabricated cavity surrounding the reactor filled with low-pressure gas offers low thermal conductivity down to approximately 0.001W/mK and can be engineered by managing pressure and cavity depth. Silicon microfabrication enables a straightforward approach to this structure as a cavity of precise depth can be etched in silicon and bonded with either silicon or glass using vacuum bonding methods. Figure 4 shows a concept for microfabricated vacuum insulation.

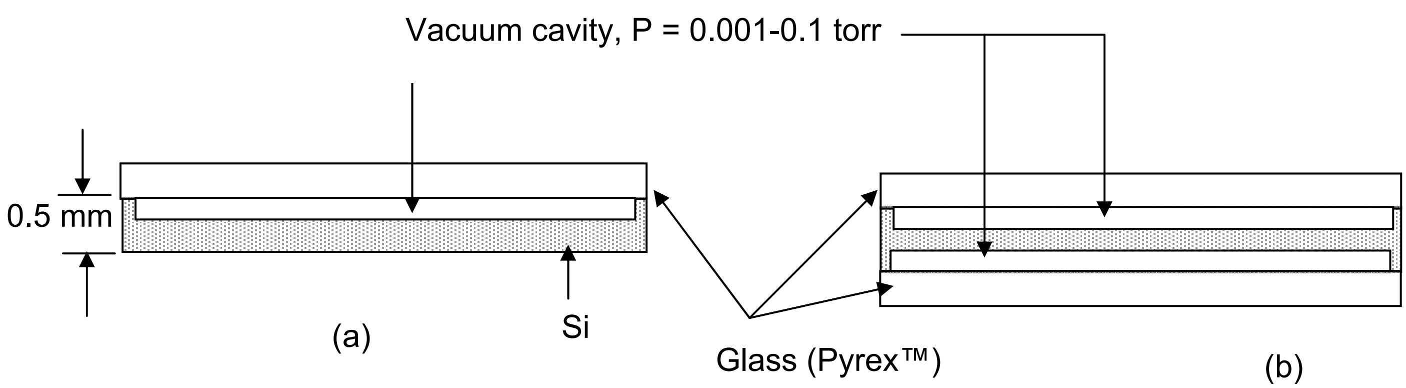


Figure 4. Vacuum insulation chip with (a) a single microfabricated cavity in Si, and (b) cavities on both sides of Si

Integrated Micro SR: Design and Fabrication

The design of an integrated SR is shown in Figure 5, where vacuum packaging chips, thin film metal heaters and temperature sensors are directly embedded with the reforming microreactor to simulate an integrated SR in an overall fuel processing scheme.

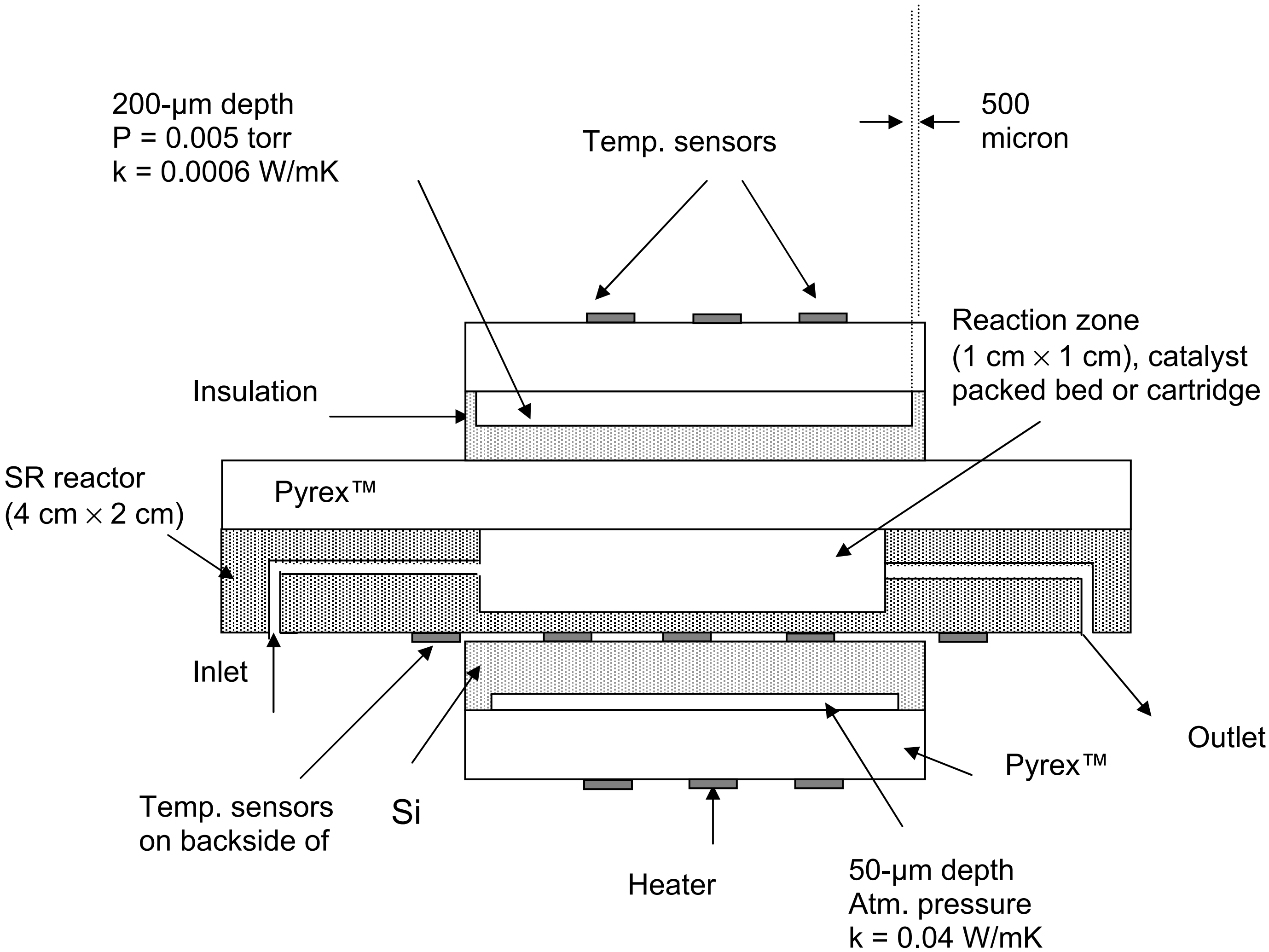


Figure 5. Design of an integrated SR

Silicon microfabrication technology is used to fabricate reforming microreactors, vacuum packaging chips, thin-film heaters and temperature sensors on silicon and glass substrates. Figure 6 shows fabricated components of this integrated device.

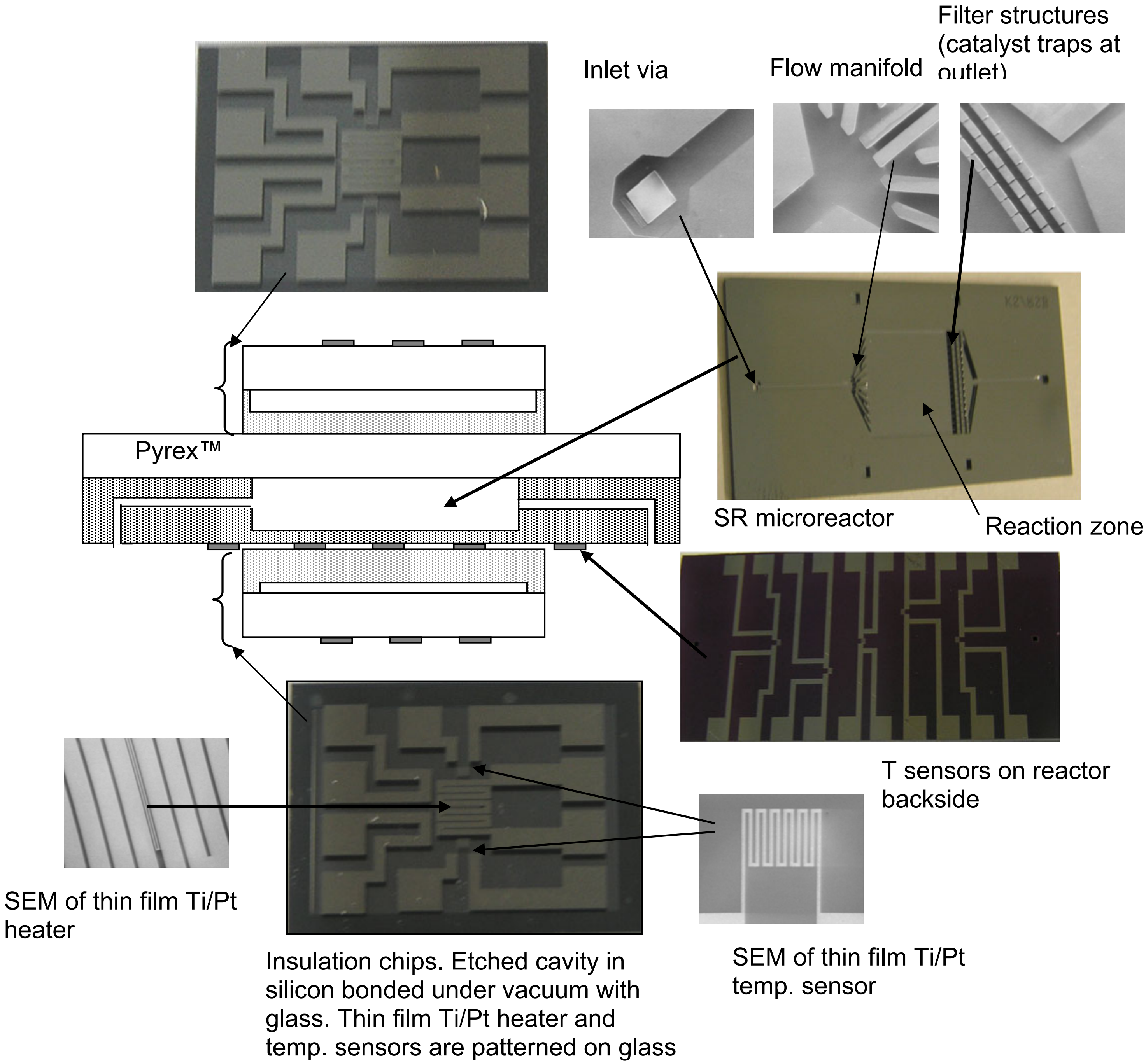


Figure 6. Fabrication of an integrated SR using silicon microfabrication techniques

The catalyst is incorporated in the form of a packed bed in the silicon microreactor chip bonded with glass. Figure 7 shows the silicon microreactor packed with catalyst particles of mean diameter 70-80 μm.

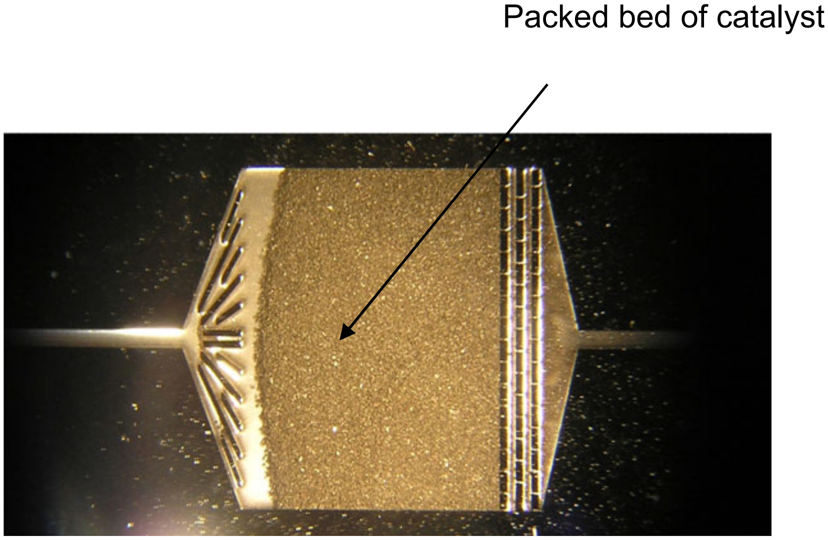
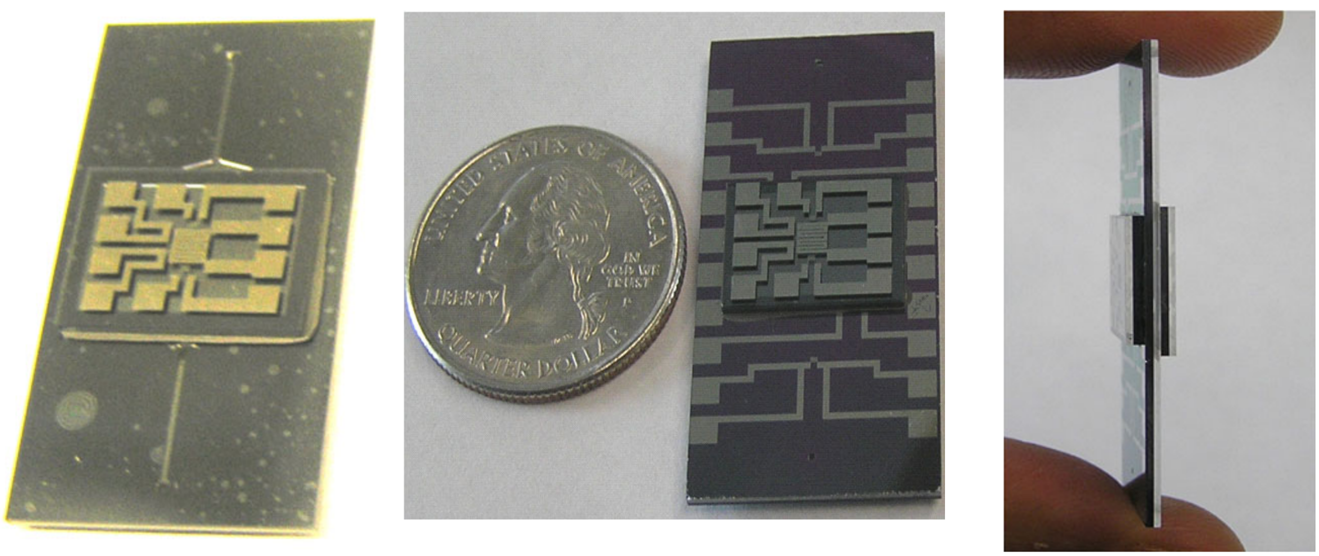


Figure 7. Incorporation of catalyst in the form of packed bed by vacuum loading
Catalyst loading achieved: 51 mg

Next, the insulation chips are bonded on the front and back sides of the catalyst-loaded microreactor using high temperature epoxy. Figure 8 shows the microreactor bonded with insulation chips.



Frontside of SR microreactor bonded with insulation chips

Backside of SR microreactor bonded with insulation chips

Assembled integrated microreaformer (six-chip stack)

Figure 8

Experiments are in progress for thermal and reaction characterization of these devices on a custom-built test setup. Well defined external heat flux is introduced to simulate the flows that result from integration with the combustor. Distributed sensors are provided to obtain the temperature profiles along the axial length. Detailed thermal data (heat input required, heat losses, temperature profiles) and reaction data (conversion and selectivity) are acquired and used to verify with the computational fluid dynamics (CFD) model for the system. Results of these experiments will be published as they become available.

Research Impact

This work will provide fundamental insight in understanding of critical thermal parameters of an integrated microreformer such as transfer of heat between reactor components, control of temperature, insulation, and heat losses. The research outcome will help conceive applications and limitations of silicon microchemical technology for micro fuel processing and provide impetus for subsequent development.

Acknowledgements

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