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6. AUTHOR(S)

Rishi Raj

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Mechanical Engineering
University of Colorado
Boulder CO 80309-0427

8. PERFORMING ORGANIZATION REPORT NUMBER

Attn: Rishi Raj

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Dr. Joan Fuller

Ceramic and Non-Metallic Materials
Program Manager, AFOSR
801 N. Randolph Street, Room 732
Arlington, VA 22203-1977

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A photo-stereolithography system, Viper si2, sold by the company 3D Systems, as described in the original proposal, was acquired in the summer of 2003. The system was delivered and installed by the vendor in June 2003. A graduate student, Tsali Cross, and a post-doctoral associate, Neil Cramer, from the College of Engineering at the University of Colorado received intensive training at the company site in California during Fall'03. Since then the lithography system has been used to build single and multilayer pre-ceramic polymer structures by UV-photopolymerization-lithography. The "mask-less" computer interface and the vertical stepping of the tray holding the organic precursor is leading to novel applications in the fabrication of single, and multilayer ceramic microsystems. Examples of these applications are included in this report.

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FINAL PERFORMANCE REPORT

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F49620-02-1-0201

To:

Dr. Joan Fuller
Ceramic and Non-Metallic Materials Program Manager
Air Force Office of Scientific Research
801 N. Randolph Street, Room 732
Arlington, VA 22203-1977

submitted via the following organization:

DTIC-OCP
8725 John J Kingman Road, Suite 0944
Fort Belvoir VA, 22060-6218
(703) 767-8023

submitted by

Rishi Raj (Principal Investigator)

Department of Mechanical Engineering
University of Colorado at Boulder
Boulder CO 80309-0427
rishi.raj@colorado.edu

February 20, 2004

Executive Summary

A photo-stereolithography system, Viper si2, sold by the company 3D Systems, as described in the original proposal, was acquired in the summer of 2003. The system was delivered and installed by the vendor in June 2003. A graduate student, Tsali Cross, and a post-doctoral associate, Neil Cramer, from the College of Engineering at the University of Colorado received intensive training at the company site in California during Fall'03. Since then the lithography system has been used to build single and multilayer pre-ceramic polymer structures by UV-photopolymerization-lithography. The "mask-less" computer interface and the vertical stepping of the tray holding the organic precursor is leading to novel applications in the fabrication of single, and multilayer ceramic microsystems. Examples of these applications are included in this report.

The holding tray for the liquid organic precursor, which is cross-linked by UV lithography, has been adapted for the fabrication of small scale systems for Ceramic MEMS. The new tray is smaller (approximately two inches on the side) and is operating satisfactorily.

The system is drawing users from Departments of Mechanical Engineering, Chemical Engineering, and (soon) from Aerospace Engineering Sciences at the University of Colorado. The system is planned to be used for laboratory experiments associated with courses, both graduate and undergraduate, in the Engineering College.

The day to day management of the system and the training of new users is in the hands of Dr. Neil Cramer, and Tsali Cross, with Professors Raj and Bowen, from Mechanical and Chemical Engineering Departments, serving as the faculty members in-charge of this very new and important addition to research and education facilities at the University of Colorado at Boulder. Off campus users interested in learning more about the system and with a desire to use the system should contact Professor Rishi Raj at rishi.raj@colorado.edu. He will be pleased to facilitate broader usage of this facility beyond the border of the Boulder campus.

Description of the Acquisition

The Viper si^2 from 3D Systems was purchased on 4/28/03. It was delivered on 5/20/03 and installed at the University of Colorado at Boulder during the week of 6/9/03. Follow-up training for users occurred on-site at 3D Systems in Valencia, CA during 8/4/03-8/6/03, and 11/10/03-11/13/03.

The specifications for the Viper si^2 from 3D Systems are as follows:

Laser	Type	Solid state Nd:YVO_4
	Wavelength	354.7 nm
	Power at vat	100mW
	Laser Warranty	7,500 hrs or 12 months (whichever comes first)
Recoating System	Process	Zephyr™ recoating system
	Minimum build layer	0.05mm (0.002in)*
	Tested build style for SL 7540 material:	0.10mm (0.004in) - EXACT™ build style*
	Tested build styles for SL 5510 material:	0.10mm (0.004in) - EXACT build style*
		0.15mm (0.006in) - QuickCast™ build style*
		0.05mm (0.002in) - HR EXACT build style*

Optical & Scanning	(diameter @ 1/e_)	Standard mode 0.250 +/- 0.025mm (0.010 +/- 0.001in) Hi res mode 0.075 +/- 0.015mm (0.0030 - 0.0005in)
Elevator	Vertical resolution	0.0025mm (0.0001in)
	Position repeatability	0.0076mm (0.0003in)
	Maximum part weight	9.1kg (20lb)
	Typical velocity during part building	5mm/sec (0.2in/sec)
Vat Capacity	Volume	32.21 L (8.5 U.S. gal)
	Maximum build envelope in standard mode	250 x 250 x 250mm XYZ (10 x 10 x 10in)
	Maximum build envelope in HR mode	125 x 125 x 250mm XYZ (5 x 5 x 10in)
	Interchangeable vat	Yes
System Controller and Software	Control software	Buildstation 5.2 software
	Operating system	Windows NT 4.0
	Input data file format	.stl and .slc
	Available fixed disk capacity	20GB
	Network type & protocol	Ethernet, IEEE 802.3 10/100BASE-T

Power	100 - 120 VAC +/-10% 50/60 Hz, 6 amps	15 amp, 115V
	220 - 240 VAC +/-10% 50/60 Hz, 3 amps	8 amp, 230V
	UPS power rating	2KVA minimum
Ambient Temperature	Temperature range	23°C +/- 3°C (73°F +/- 5°F)
	Maximum change rate	1°C/hour (3.4°F/hour)
	Relative humidity	20 - 50%, non condensing
Size	Crated machine	W168 x D102 x H211 cm (W66 x D40 x H83in)
	Uncrated machine	W134 x D86 x H178 cm (W52.5 x D33.5 x H70in)
Weight	Crated Process Module	564 kg (1,242 lb)
	Uncrated process module	463 kg (1,020 lb)
Options	Additional interchangeable vats Additional build platforms Post Curing Apparatus (PCA™) equipment	
System warranty	One year from installation date. Includes parts, labor, and 3D Systems' software upgrades.	

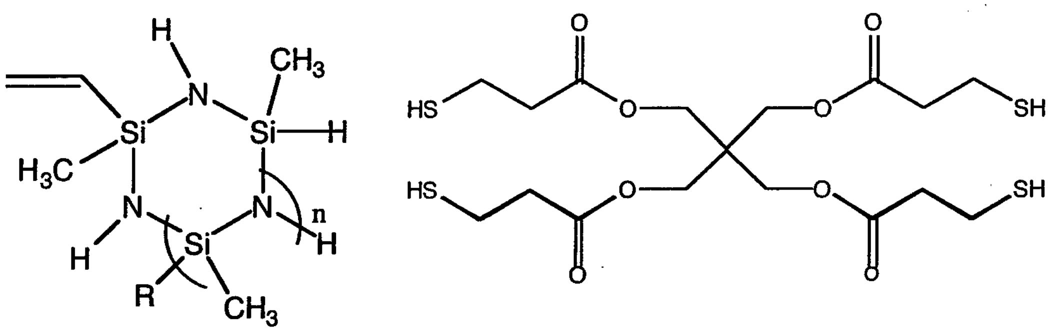
*Dependent upon part geometry, build parameters and material.

Standards and Regulations: This SLA system conforms to Federal Laser Product Performance Standards 21CFR1040.10 Class I laser in normal operation. During field service emission levels can correspond to Class IV laser product. The Viper si^2 system complies with CE requirements.

For further specifications: http://www.3dsystems.com

Polymer Systems for Ceramic MEMS

Polymer derived MEMS necessitate the use of novel resin systems with specialized properties. The resin systems that are primarily being investigated are organic precursors to polymer derived ceramics (PDC's). They involve using polysilazane monomers (VL-20™ and Ceraset™, Kion Corp.), a thiol monomer, and a photoinitiator (Figure 1). The resin is both costly and unstable for long periods of time. Also, the MEMS devices being developed in this research are very small, being on the order of 1 cm^2 and several hundred microns in height.



(a) (b)

Figure 1: Monomers utilized in resin for polymer derived ceramics, (a) VL20, where R = H, CH_3, or $CH{=}CH_2$ and n = 1-20, (b) pentaerythritol tetra(3-mercaptopropionate) (thiol).

MEMS devices are created by building the device one layer at a time via photopolymerization. A drawing of the device to be built is loaded into the 3D systems software where it is sliced into individual layers. The layers are then drawn one at a time with a 355 nm laser that initiates a photopolymerization transforming liquid resins into a solid polymer.

Examples of Use and Results

The fabrication of PDC devices required using the Viper si^2 in an unconventional manner in order to allow for calibration of a novel resin and accommodate building with small quantities of resin. Ordinarily, the Viper si^2 requires approximately 20 lbs of resin to build. It was impractical to fill the vat with PDC resin due to rapid degradation of the liquid PDC in air. In order to build with small quantities of resin, the approach taken was to break down the fabrication of complex three-dimensional devices into three steps:

- single-layer devices,
- simple multi-layer devices, and
- complex multi-layer devices.

Single-layer devices

Single-layer devices are the simplest to fabricate. The general process is shown in Figure 2, where the build style was modified to build single layers at a time. As shown in Figure 2, a small Petri dish with a silicon wafer resting on the bottom of the dish is filled with resin. The Petri dish with wafer and resin is placed on the build platform. The laser draws the image by moving in the X-Y plane, in accordance with a pattern (which can be generated with almost any CAD software). Free radical-photopolymerization causes solidification of a shape from the irradiated laser path.

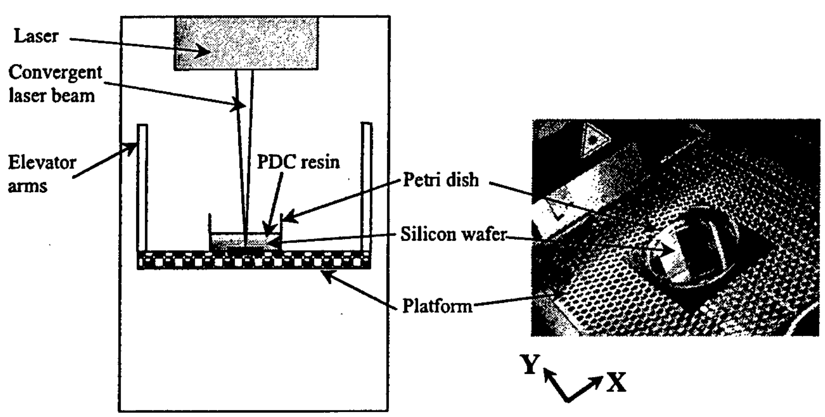


Figure 2: General process for fabrication of single-layers from small quantities of resin.

Sufficient experience was gained and precision was demonstrated in building somewhat complex single layer devices from CAD generated designs, as shown in Figure 3.

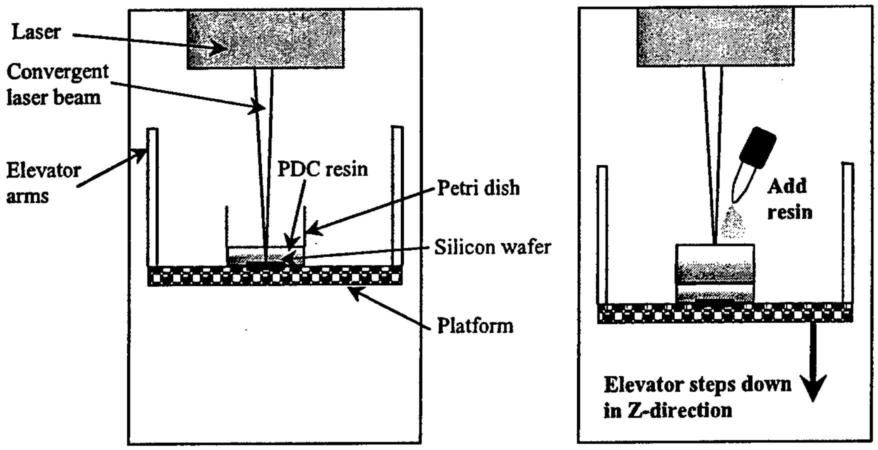
(a) (b)

Figure 3: Single-layer shapes generated from CAD software demonstrating sufficient precision. (a) CAD software design. (b) Resulting polymeric shapes. *The bar in the bottom right corner equals 1 mm.*

Simple multi-layer devices

Adding more layers with more intricate geometries increases the allowed complexity of device design. The general process for multi-layer devices is shown in Figure 4 and is termed "the Petri dish process". The first layer is built as previously described for single-layer devices. The second layer is added by moving the elevator attached to the platform in the Z-direction down to a user-inputted height. Additional resin is added into the Petri dish with a dropper such that the resin is approximately level to the focal point of the convergent beam.

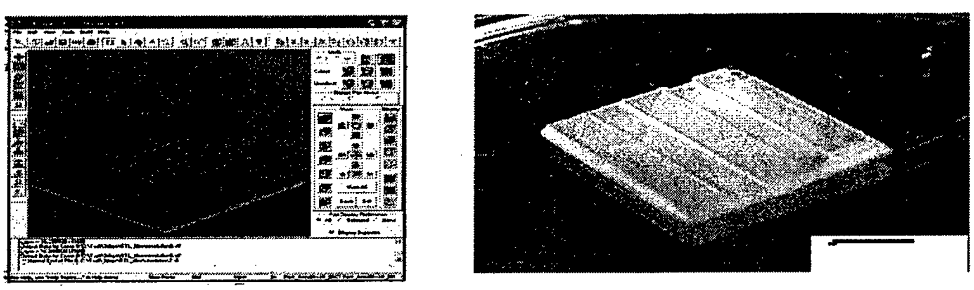
"The Petri Dish Process"



Build 1st layer *Build 2nd layer on top*

Figure 4: General process for building simple multi-layer devices, "the Petri dish process".

Figure 5 shows a simple multi-layer device that was fabricated. The device may be adapted for use as an optical transmission grating or the channels for a microfluidic device.



(a) **(b)**

Figure 5: Device fabrication for a simple multi-layer device. (a) CAD software design. (b) Resulting polymeric device. *The bar at the bottom right corner equals 1 mm.*

Complex multi-layer devices

Complex multi-layer devices were fabricated in the same way as simple multi-layer devices. Complex geometries were achieved at this step primarily due to increased precision in calibration of our novel resin system due to experience. A micro-rocket nozzle was fabricated as shown in Figure 6.

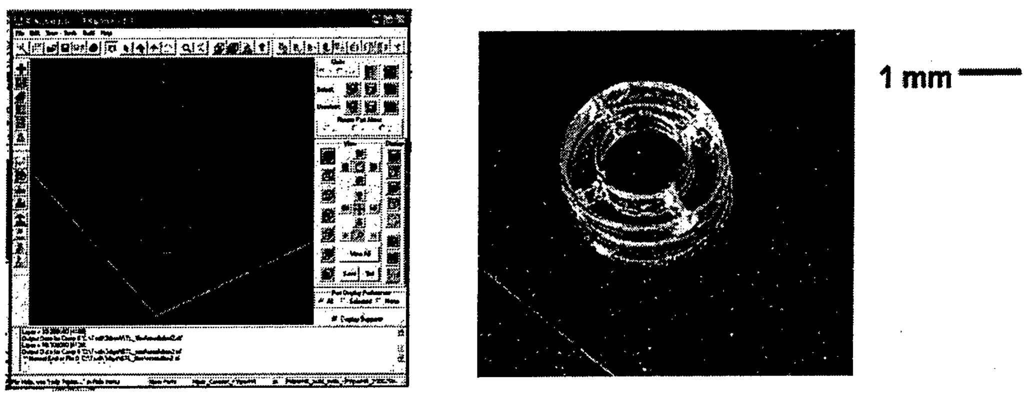


Figure 6: A micro-rocket nozzle was fabricated demonstrating high precision and complex geometries.

This fabrication process can be used to generate microcombustion chambers and many other microfluidic devices, as well as systems requiring high surface area to volume ratios. However, the Petri dish process has a major limitation. The most significant problem with this fabrication process is the lack of depth control and it was also impractical to build complex devices that may have tens or hundreds of layers. Modification of the Viper si^2 system was necessary in order to build parts with very small quantities of resin while maintaining the system's ability to control layer thickness with great precision (~25 μm per layer).

Modification of Viper si^2

The vat size, delivered with the system, is more suited for industrial use. Therefore a smaller vat, approximately two inches deep, was acquired for our research. This modification of the Viper si^2 accomplishes four goals:

- Fabrication of precision devices with many layers
- Calibration of each resin,
- Use multiple resins, and
- Use small quantities of resin.

Each resin system must be calibrated such that input files or drawings are accurately transformed into polymeric devices. The energy required for cure, laser penetration depth, and build styles determine how accurately the resin is transformed into a polymeric device. All of the parameters are resin specific and must be calibrated for each new resin.

The Petri dish process does not allow for accurate layer thickness control, which is integral to calibration, and involves time-consuming re-fillings of the Petri dish for each successive layer. All of these problems were overcome through the design and fabrication of a smaller, self-leveling vat, a smaller build platform, and initial z-control stage. The fabricated components and assembly are shown and labeled in Figure 7.

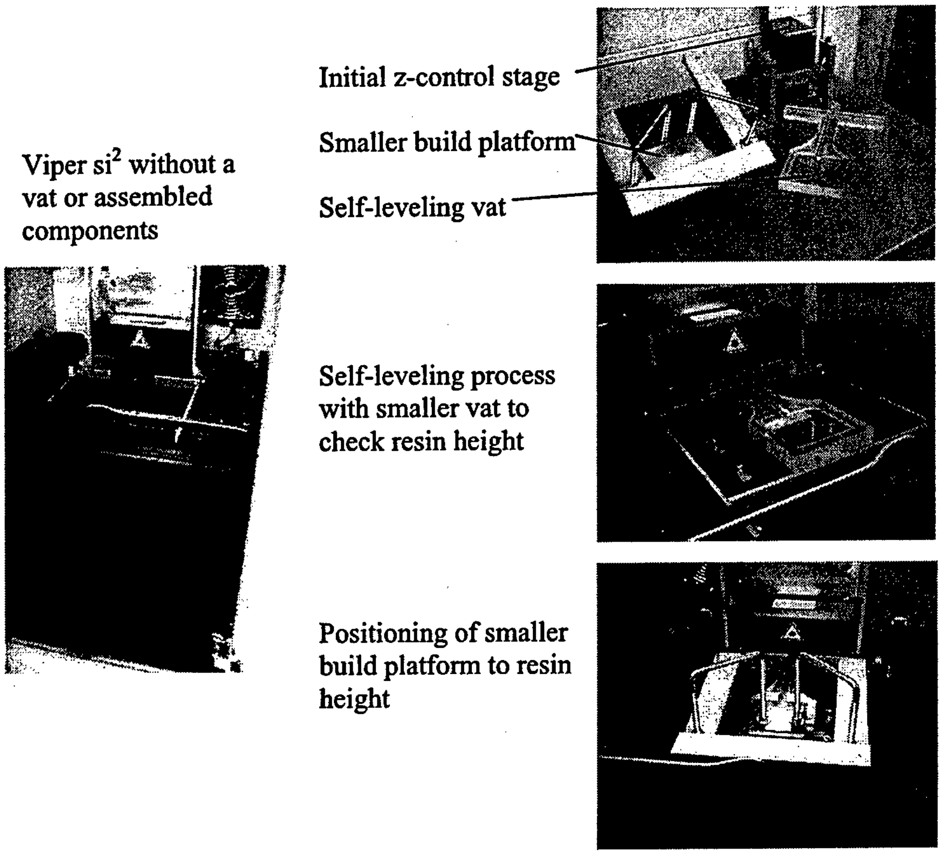


Figure 7: Fabricated components for the modification of the Viper si^2.

A general illustration of the fabricated components and function are shown in Figure 8. The design takes advantage of the Viper si^2's ability to check resin level height with a laser and optical detector, as well as its ability to move the platform to the detected resin level height. Shown in Figure 8 (a), the first step of the process is to adjust the initial z-control stage controlled by a Vernier gage, to bring the resin to operating level, at which point the resin level height can be determined with a laser and detector near the back of the Viper si^2. The platform fitted with the smaller build platform moves to the top of the resin level with enough resin on top for the first build layer (Figure 8 (b)). Upon completion of the first build layer, the platform moves down into the resin reservoir such that a second layer can be built on top of the first (Figure 8 (c)). The process then repeats itself until all build layers of the part are complete.

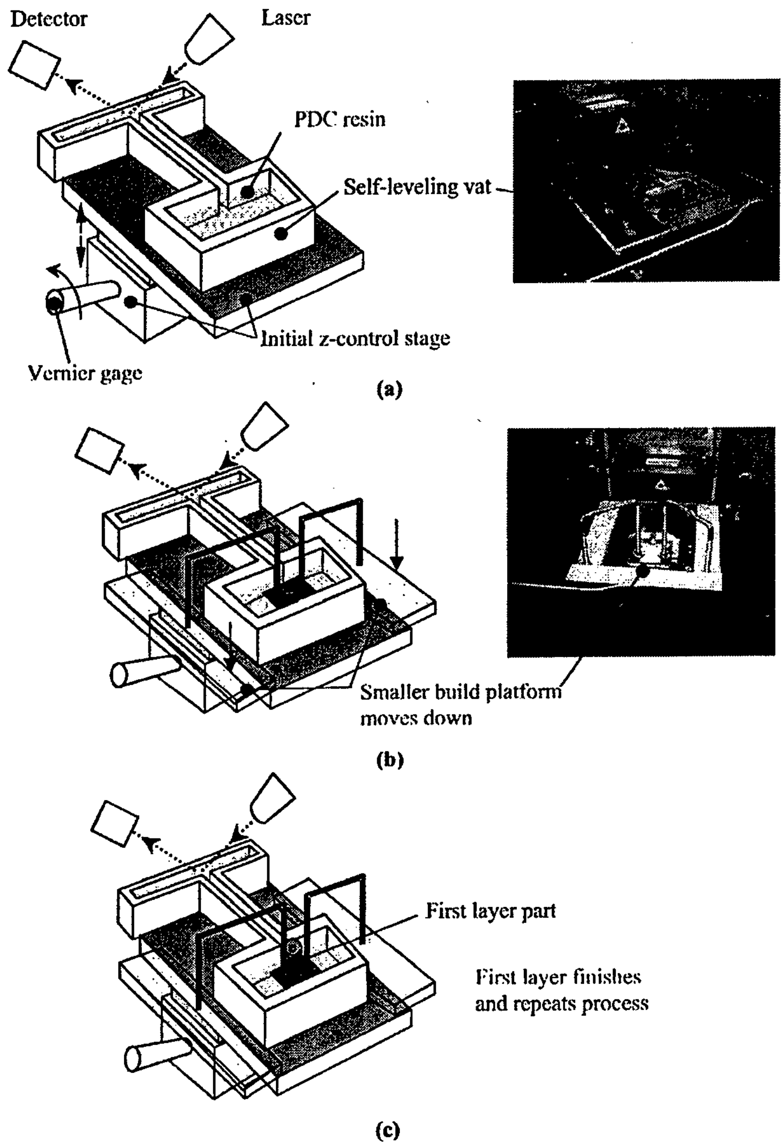


Figure 8: Fabricated components and function for modification to calibrate and build with small amounts of resin. (a) The resin level height is detected. (b) The platform moves to the resin level height. (c) After the first layer builds, the platform moves down into the resin reservoir and a second layer builds. The process is repeated until completion of part.

Projects and research, current and planned

The Viper si^2 system can also be utilized in an unmodified capacity to generate polymer devices from pre-calibrated resins purchased from 3D Systems. The following projects are under evaluation for collaboration with other researchers at the University.

Professor Rishi Raj (Department of Mechanical Engineering)

The following grants are intense users of the stereo-photolithography facility.

• AFOSR-MEANS Program: *Novel SiCN Ceramics for Health Monitoring of High Temperature Systems.*
• DOE: *A Novel Polymer-Derived Nano-Ceramic for Ultrahigh Temperature MEMS.*

Professor Davis (Chemical engineering)

• Low-Reynolds-Number Particle Transport in Narrow Channels for Microfluidics and Other Applications
• Manufacture custom ellipsoidal particles for use in particle-tracking experiments. The particles would be used to verify the results of a simulation of the motion of ellipsoids in low-Reynolds-number flow, which would be applicable to manipulation of nonspherical cells in microfluidic devices and other applications.

Professors Bowman and Davis: (Chemical Engineering)

• Interfacing microfluidic devices with external equipment (DARPA).
The goal of this project is to develop a top layer for polymeric microfluidic devices that easily interfaces with external equipment, such as syringe pumps. Once a universal design is developed, the 3D Viper system will be ideal for mass production of these microfluidic components.

Professor Bob McLeod: (Electrical Engineering)

• Hybrid Integrated Photonics

The Viper will be used to create millimeter-scale polymer scaffolds for micro-optic integrated circuits. The combination of quick turn-around and nearly arbitrary 3D structures will allow us to rapidly fabricate and test new circuit concepts.

Broad Impact on Institutional Infrastructure

The Viper system made possible by the DURIP grant has established a new and unique facility at the University of Colorado, and most likely in the entire state of Colorado (indeed, there are very few Viper systems located at Universities for research and educational purposes around the world). The Viper system represents the state-of-the-art in photopolymerization and MEMS fabrication technology and promises to extend microsystem fabrication beyond polysilazane-derived materials to a wide variety of novel photopolymerizable sol-gels, preceramics, and photopolymers. The benefits of combining students' learning and creativity to develop undiscovered MEMS devices are invaluable.

Immediately, the Viper si^2 can be used in classroom settings as a demonstration or in laboratories to increase or enhance curricula and hands-on-learning. Demonstrations and laboratories for consideration are:

- Design and fabrication of a polymerase chain reaction microfluidic chamber
- Principles of stereolithography (rapid prototyping)
- Principles of photopolymerization
- Cure depth and applications to design and manufacturing
- CAD design for stereolithography
- Prototype development and visualization