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Rapid prototyping of a micro pump with laser micromachining

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ABSTRACT

A micro electrohydrodynamic (EHD) injection pump has been developed using laser micromachining technology. Two designs have been fabricated, tested, and evaluated. The first design has two silicon pieces with KOH-etched wells which are stacked on the top of each other. The wells are etched on one side of the wafer and gold is deposited on the other side to serve as the pump electrodes. A Nd:YAG laser is used to drill an array holes in the well region of both silicon die. This creates a grid distribution with a rectangular pattern. Next the well regions of the die are aligned, and the parts are bonded together using a Staystik thermoplastic. The pump unit is then mounted into a ceramic package over the hole drilled to permit fluid flow. Aluminum ribbon wire bonds are used to connect the pump electrodes to the package leads. Isolation of metallization and wires is achieved by filling the package well and coating the wires with polyimide.When a voltage is applied at the electrodes, ions are injected into the working fluid, such as an organic solvent, thus inducing flow. The second design has the die oriented 'back-to-back' and bonded together with stayform. A 'back-to-back' design will decrease the grid distance so that a smaller voltage is required for pumping. Preliminary results have demonstrated that this micro pump can achieved a pressure head of about 287 Pa with an applied voltage of 120 volts.

KEYWORDS: micro-pump, laser micro-machining, MicroElectroMechanical Systems, electrohydrodynamic pump, micro heat sink.

1. INTRODUCTION

Recent advances in the fabrication of silicon microstructures have created a new technology known as Micro-ElectroMechanical Systems (MEMS). If these MEMS devices are incorporated into an engineering system, the integrated unit can be built smaller, lighter, and smarter. The manufacturing cost of MEMS can be low because they can be made in large quantities. Thus, the cost of MEMS devices is dominated by the development cost. Current techniques for producing MEMS structures use photolithography techniques. These include silicon micro-machining using wet and dry etch, Excimer laser micromachining, and LIGA (Lithographie, Galvanoformung, Abformung). All these methods require high capital cost, special equipment, and facilities. Hence in order to reduce the development cost, MEMS researchers and engineers have been looking for ways to shorten the 'research-to-production' cycle and to reduce the development time.

At Sandia National Laboratories, we are working towards a system integration process for MEMS devices[1]. This integration process involves five phases: project goal and definition, design and development, fabrication, test and evaluation, and final product development. Because of the exploratory nature of MEMS research, a few iterations are needed in order to achieve a satisfactory final product. Our goal is to expedite the integration process by incorporating computational modeling into the design loop. To demonstrate how this integration would work, we are designing and building an active cooling system for microelectronics application. It has the following components: a field array of temperature sensors to locate local hot spots, thermally driven micro-actuators, micro-pumps and micro-channels. This cooling system can be considered as a 2-loop heat exchanger. Our initial effort is to develop and test single components then follow-on with the system integration. Since this is an ambitious task, our desire is to rapidly prototype these single components and to evaluate our design concept quickly. This paper addresses the design and fabrication of a micro electrohydro-dynamic (EHD) injection pump by utilizing the laser micromachining process and material bonding. This allows us to achieve a quick turn-around time and develop a economic prototyping process.

2. LASER MICROMACHINING

Laser micromachining offers a method to bridge the gap between the resolution obtainable by conventional mechanical machining operations and chemical micromachining techniques. Using conventional machining processes, it is extremely difficult, if not impossible, to produce machine components with structures several mils (1 mil ≈ 25 microns) in size with tolerances of a quarter of a mil. Chemical micro-machining techniques allow much smaller structures to be produced; these techniques have several limitations in both materials that can be machined and in obtaining high-aspect-ratio geometry. In general, chemical micro-machining techniques are a planar technology and rely on isotropic etchants to remove the excess material. Thus, material is removed uniformly from the substrate in all directions. However using this chemical micromachining process to develop and fabricate a conceptional micro-device does take time and is relatively expensive. For bulk micromachining processing, laser micromachining has the distinct advantage of being able to produce high aspect ratio geometry with micron, or several micron resolution. In addition, the laser process is applicable to broad range of materials and the laser wavelength can be modified to insure optimum coupling of the laser radiation to the material being machined. Usually the laser process has a faster turn-around time and is relatively cheaper for use in the development of a conceptional micro-device.

Sandia has acquired Nd:YAG laser technology, a new technology, that is well suited for rapid prototyping. Unlike excimer lasers that have a large up front cost as well as potential environment, safety, and health concern due to the toxic gases involved, the Nd:YAG laser is cost effective to operate and acquire. Moreover the Nd:YAG laser will allow the operational wavelength to be converted to several frequencies from the near infrared portion of the spectra to the ultraviolet portion of the spectra.

The Nd:YAG laser system was originally designed to process silicon of varying thickness, hole diameters, and geometries. Initially all work was accomplished at the fundamental wavelength (λ) of 1064 nm. Creation of through holes at 1064 nm is done by a small percentage of vaporization and a large percentage of silicon (Si) melting. Most of the fabrication done for the micro pump work had been using this wavelength of 1064 nm for a quick turn-around time. Through various experimental procedures and cross-section evaluation it was determined that the absorption coefficient at this λ for Si was not optimal for laser machining. If any improvement is needed, the laser system could be modified to produce the second harmonic λ of 532 nm. Second harmonic generation (SHG) was produced using intra-cavity frequency doubling with a non-linear crystal.

The development of SHG was done specifically to laser process Si. This was due to two primary reasons. First, the absorption coefficient in Si at the 532 nm λ is approximately 2 times greater than at the 1064 nm λ. Secondly, the focused spot size at this wavelength is ≈ 12 μm. Observing the equation for spot size, i.e. *spot size* = $(4\lambda/\pi)$ x (*focal length / beam diameter*), the focused spot size for SHG becomes half the diameter of the 1064 nm λ focused spot size. The combination of greater energy absorption in Si at the 532 nm λ combined with the significantly smaller focused spot size creates a mechanism of vaporization and ablation to remove Si material. This is due to a significant increase in absorbed power density. The calculated irradiance at the sample for the 532 nm λ is 5.8×10^9 watts/cm^2 based on a repetition rate of 4kHz and a pulse width of 150 nsec. The 532 nm λ proved to be very efficient in laser machining silicon with minimal debris and side wall micro-cracking in the through hole.

The next major development in the laser system was to design a system capable of fourth harmonic generation (FHG) to produce an output beam in the ultraviolet at 266 nm λ. This would allow simultaneous drilling through Si and organics. The development of the fourth harmonic generation included a combination 4th harmonic crystal holder with focusing lenses, optical wavelength separator and ultraviolet up-collimator. The average output power at the 266 nm λ was approximately 400-600 milliwatts, and irradiance per pulse ≈ 2.35×10^9 watts/cm^2. As a result of numerous process requirements, a laser system was developed with extensive machining capabilities, due mainly to the capability of utilizing wavelengths ranging from the near infrared, through the visible, to the ultraviolet.

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3. DESIGN OF AN EHD INJECTION PUMP

Designing and fabricating a micro pump for the microelectronic applications is a challenging task. The design requirement is to extract heat from the hot spot region in a multiple-chip module at about 50 Watt/cm^2. This implies the volumetric flow rate in a micro-channel to be in the order of 5 milliliter per minute. Several existing micro-pump designs have been investigated. These include membrane pumps[2-4] as well as pumps without moving parts[5-7]. Most pump design can achieve a pumping rate of several hundred microliters per minute; only a few design can reach a pumping speed of milliliters per minute. One pump design that is very attractive to us is an electrohydrodynamic injection pump[7], also known as an ion drag pump. The principal behind the ion drag pump[8] is as follows: consider two screen electrodes are placed at a distance apart inside a circular cylindrical conduit with an insulating wall. Charged particles are uniformly injected into a nonconductive fluid at the upstream electrode and then collected at the downstream electrode. These charged particles are ions generated by a corona discharge. The motion of the charged particles, as they are traveling across the electrodes, will drag the fluid particles along, thus creating pumping motion. This section will present the progress made using this electrohydrodynamic principal to build and test a micro pump.

3.1. First iteration: a stacked geometry

The first pump design uses two stacked silicon wells which are drilled for grid formation and metallized on one side for electrical contact (Fig. 1 and Fig. 2). The wells are formed with a KOH etch, then drilled from the well side to create a grid structure. Hole sizes for the grid are about 0.003" to 0.004" (76 μm to 102 μm) and spaced about 0.005" (127 μm) apart. Well dimensions are 0.180" x 0.150" (4.57 mm x 3.81 mm) and 0.009" (229 μm) deep into 0.012" (305 μm). The bottom die is cut to 0.340" x 0.340" (8.64 mm x 8.64 mm) and the top die is cut to 0.310" x 0.340" (7.87 mm x 8.64 mm) to allow room at the edge for wire bonding. Staystik 383, a nonconductive thermoplastic, is used to join the top and bottom die along the well perimeters. Using the same Staystik adhesive, the assembled unit is mounted into a 40 pin DIP that has a 0.150" (3.81 mm) diameter hole laser drilled through the bottom of the package cavity. Aluminum ribbon wire (0.020" x 0.001" or 508 μm x 25 μm) is tacked on to the pump electrodes and connected to package leads. Polyimide (MicroSi 115) and Staystik 383 is used to filled the package cavity and coat wire bonds. This isolates the wires and metal layers to prevent shorting through the fluid at higher voltages that was observed as the failure mechanism of uninsulated pumps. Wires are also attached to opposite sides of the package to eliminate shorting between the wires. Since lower voltages can be used to obtain pumping if the grid distance (Figs. 1 and 2) is reduced, several pumps were constructed with thinner top die (with thicknesses of 0.006" and 0.004", i.e. 153 μm and 102 μm). This reduces the grid distance from 0.013" (330 μm) to 0.007" (178 μm) and 0.005" (127 μm), respectively. Grid distance is equal to the top die thickness plus approximately 0.001" (25 μm) for the adhesive layer. The process flow for the stacked pump is given in Table 1.

Next these stacked micro-pumps are being tested and evaluated for their performance. The working fluid being used for the tests is propanol, an organic solvent. Preliminary results of the tests show that these micro-pump can pump fluid and produce a pressure head. A design with 4-mil (102 μm) holes and 6-mil (152 μm) grid distance demonstrates that pumping starts at about 60 Volts. This is somewhat consistent with other EHD micro-pump design. More discussion of the testing and evaluation will appear in section 4. All these results have been fed back to the development process for any design improvement.

3.2. Second Iteration: A Back-to-Back Geometry

The objective of the back-to-back design was to minimize the grid distance and the corresponding operation voltage. In this design, the same drilled and metallized silicon well pieces were used except that both top and bottom die had the rectangular 0.310" x 0.340" (7.87 mm x 8.64 mm) dimensions. The metallized portions were mounted toward each other, separated by a layer of nonconductive Stayform adhesive (Stayform 421). The Stayform was cut to dimensions of 0.290" x 0.340" or 7.37 mm x 8.64 mm (with a window in the grid region to allow fluid flow) and attached to the die as shown in Fig. 3. Initially, a layer of Stayform was placed between the die prior to drilling, but laser drilling through different materials caused cracking of the die around the exit hole (Fig. 4). Without a layer of Stayform, the laser-drilled holes are relatively clean and no cracking is observed.

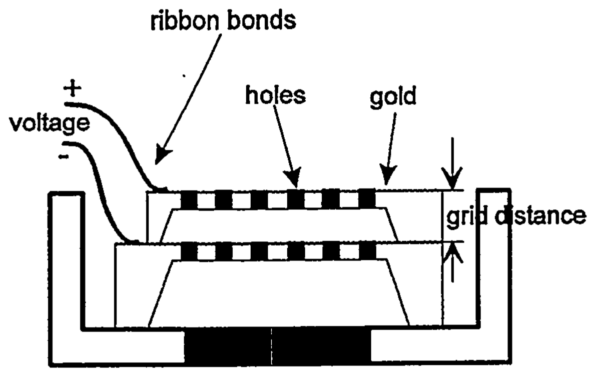

Figure 1. Cross sectional diagram of stacked geometry induction pump.

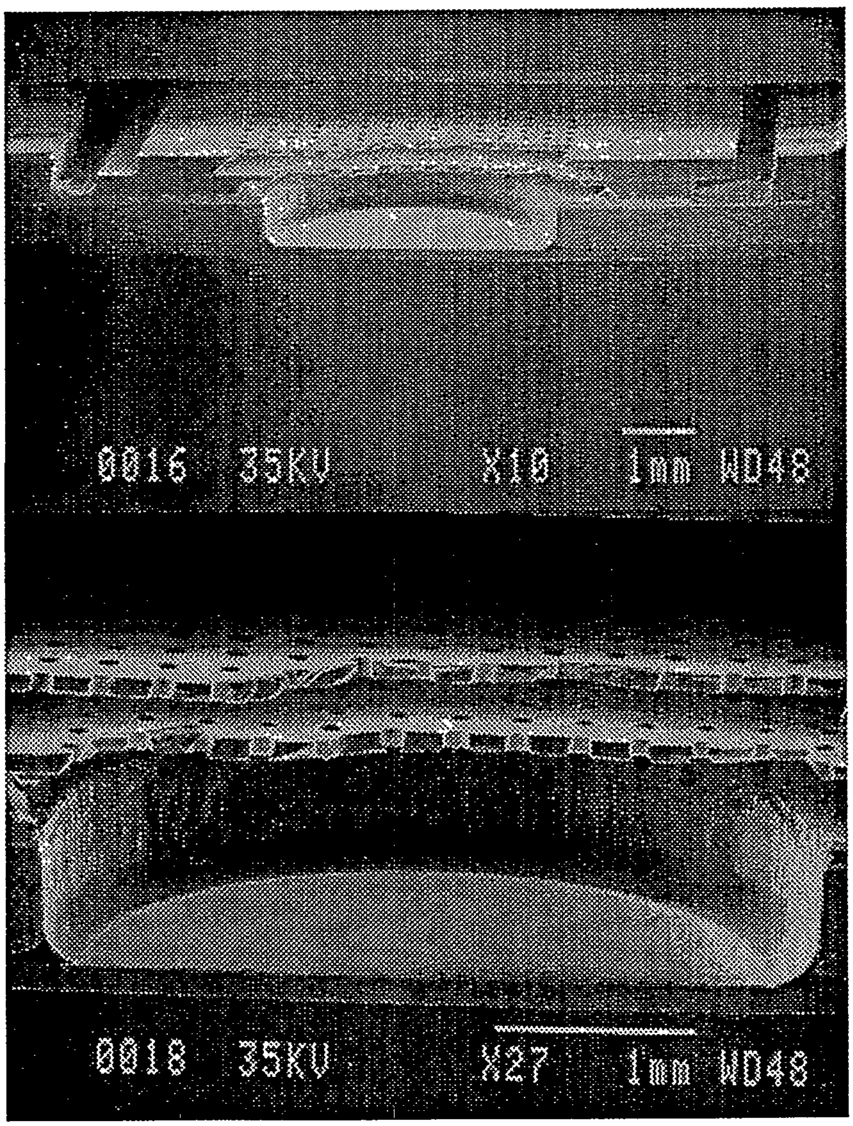

Figure 2. Cross-sectional photographs of assembled stacked pumps.

Table 1. First iteration EHD pump design (stacked version) -- Process flow

Part description: Silicon pieces with KOH-etched wells

- dimensions of bottom part: 0.340" x 0.340" (8.636 mm x 8.636 mm)
- dimensions of top part: 0.310" x 0.340" (7.874 mm x 8.636 mm)
  [take a 'bottom' part and cut one edge in 0.030" (176.2 µm)]
- both parts have gold deposited on front side (well side = back side)
- thickness = 0.012" (304.8 µm)
- well depth = 0.009" (228.6 µm)
- well size ≈ 0.180" x 0.150" (4.572 mm x 3.81 mm)

1. drill grid into top and bottom parts
   - wavelength = 1064 nm w/ O_2, from back (well) side
   - hole size = 0.003" or 0.004" (76.2 µm or 101.6 µm)
   - spacing ≈ 0.005" (127 µm)
   - ultrasonic clean to remove debris
2. thin top die to decrease grid distance (top die is 0.004" or 0.006", i.e. 101.6 µm or 152.4 µm)
   - optional step; smaller grid distance ⇒ less voltage required for pumping
3. drill 0.150" (3.81 mm) diameter hole in center of package cavity (40 pin DIP)
   - package cavity = 0.370" x 0.370" (9.398 mm x 9.398 mm)
4. assemble pump
   - join top and bottom parts using Staystik 383 (non-conductive thermoplastic)
   - apply Staystik to the edge of the top part (along well perimeter)
   - aligning parts properly should also align pump grids (three sides should match up)
   - cure: 160 °C, 10 min.
5. die attach
   - apply Staystik to the bottom of pump unit (back edge of bottom die)
   - align grids over hole in package
   - cure: 160 °C, 10 min.
6. wire bond: Al ribbon wire
   - thickness = 1 mil (25.4 µm), width = 20 mil (508 µm)
   - bond bottom part to pin 1, top part to pin 21
7. isolation of metallization and wires
   - fill package cavity and coat wire bonds with Staystik 383 or polyimide (MicroSi SP115)
   - allow to air cure & reapply insulative material to fill any gaps which formed during air cure
   - cure: 160 °C, 10 min. (Staystik); 175 °C, 1 hr (polyimide)

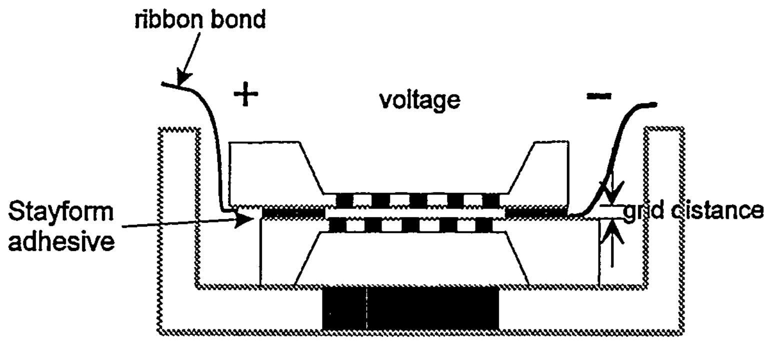

Figure 3. Cross-sectional view of the back-to-back EHD pump.

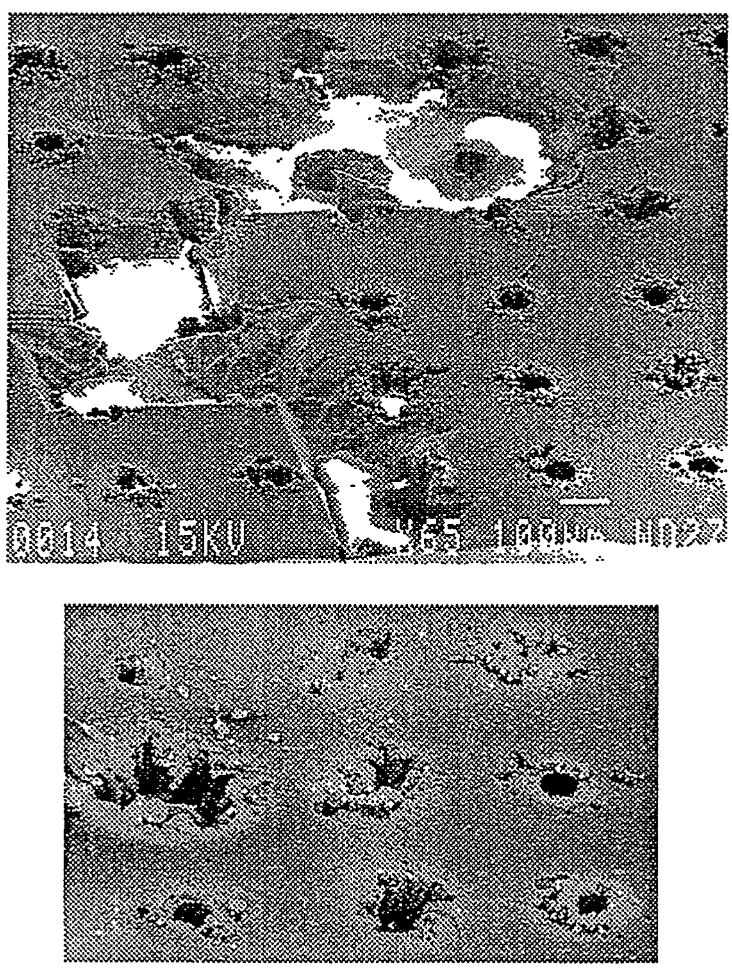

Figure 4. Exit hole cracking and damage when laser drilling two layers of silicon and Stayform 421 between the two layers.

Table 2. Second iteration EHD pump design (back-to-back version) -- Process flow

Part description: Silicon pieces with KOH-etched wells

- dimensions of top and bottom part: 0.310" x 0.340" (7.874 mm x 8.636 mm) [the 'top' part of the first iteration pump]
- both parts have gold deposited on front side (well side = back side)
- thickness = 0.012" (304.8 μm)
- well depth = 0.009" (228.6 μm)
- well size ≈ 0.180" x 0.150" (4.572 mm x 3.81 mm)

1. drill grid into top and bottom parts
   - wavelength = 1064 nm w/ O_2, from back (well) side
   - hole size = 0.003" or 0.004" (76.2 μm or 101.6 μm)
   - spacing ≈ 0.005" (127 μm)
   - ultrasonic clean to remove debris

2. drill 0.150" diameter hole in center of package cavity (40 pin DIP)
   - package cavity = 0.370" x 0.370" (9.398 mm x 9.398 mm)

3. assemble pump
   - join top and bottom parts using Stayform 421 (insulative film adhesive)
   - cut Stayform piece to 0.340" x 0.290" (8.636 mm x 7.366 mm) with a window for the grid region [approx. 0.180" x 0.0150" (4.572 mm x 0.381 mm)]
   - align parts so that the 0.340" (8.636 mm) edges match up, but the 0.310" (7.874 mm) sides allow for a 0.030" (0.762 mm) shelf on both sides for the ribbon bonds
   - cure: 250 °C, 1 min. on a hot plate, while applying slight pressure

4. die attach
   - apply Staystik to the bottom of pump unit (back edge of bottom die)
   - align grids over hole in package
   - cure: 160 °C, 10 min.

5. wire bond: Al ribbon wire
   - thickness = 1 mil (25.4 μm), width = 20 mil (508 μm)
   - bond bottom part to pin 1, top part to pin 21

6. isolation of metallization and wires
   - fill package cavity and coat wire bonds with Staystik 383 or polyimide (MicroSi SP115)
   - allow to air cure & reapply insulative material to fill any gaps which formed during air cure
   - cure: 160 °C, 10 min. (Staystik); 175 °C, 1 hr (polyimide)

After the pump is assembled, one end of the wire attached to the top die must be tacked onto the top die before the unit is turned over and attached to the package with Staystik. The other end of the wire is then attached to package, and the second wire is bonded as usual. A complete process flow is given in Table 2. Testing and evaluation is also performed on this pump design. Preliminary results will be presented in the next section.

4. PRELIMINARY RESULTS OF THE EHD INJECTION PUMPS

Currently we are testing and evaluating the performance of different micro-pumps. Any test results will be fed back into next design iteration. This section presents the preliminary results of a micro-pump with the 'back-to-back' design. This micro-pump has a 4-mil (102 μm) grid size and spacing and a 4-mil (102 μm) grid distance. More test results for other micro-pumps can be found in Reference 1. Figure 5 shows a schematic diagram of the setup to measure the static pressure in the micro electrohydrodynamic injection pump experiment. The working fluid for this test is proponal.

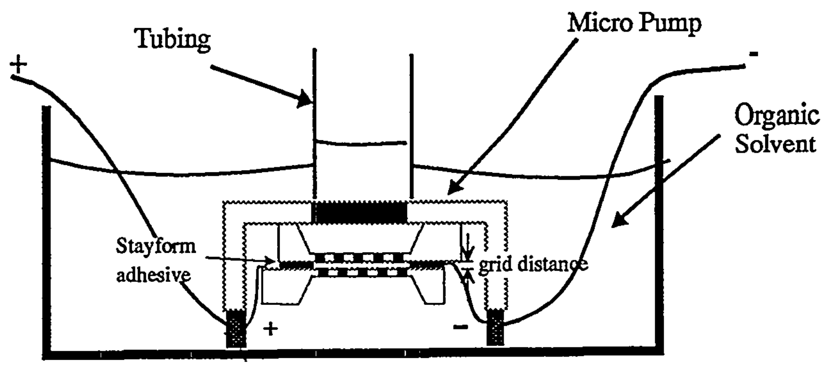

Figure 5. Setup of the Micro Electrohydrodynamic Injection Pump Experiment.

In this static pressure test, an increment of electrical voltage is applied across the electrodes to induce flow. Since one of our major interest is to measure the static pressure head that the micro-pump generates with different voltage, we bond a pipette to the outlet of the micro-pump unit and observe the rise of the liquid level with different applied voltage. The induced pressure head as a function of the applied voltage is plotted in Figure 6. No liquid level rise is observed until the applied voltage is above 40 volts. However at 50 volts and up to 120 volts, a pressure increase of 19 Pa up to 287 Pa is obtained. This is somewhat consistent with Richler's experiment[9]. The measured pressure head of 280 Pa implies that this micro pump can produce a volumetric flow rate of about 2.5 milliliters per minute across a square micro-channel of 1 cm long and 100 μm wide.

5. SUMMARY

As part of a system integration project of micro-devices, we have developed and demonstrated an electrohydrodynamic injection micro pump using a laser micro-machining technology. Our goal is to rapidly prototype and test single components so that we can speed up and shorter the development-to-production cycle. Eventually our deliverable will be an active built-in cooling system for microelectronic applications. Two designs have been investigated. The first design has the silicon die stacked on top of each other and the second design has the silicon die bonded back-to-back together. A Nd:YAG laser is used to drill an array holes in the well region of both silicon die. This creates a grid distribution with a rectangular pattern. The purpose of the second design is to reduce the grid distance so that a smaller voltage can be applied to induce flow. Preliminary results show that the second design qualitatively generates a higher pressure head. More tests are underway to further evaluate the two designs and also the influence of different grid size, grid spacing, and grid distance. For the micro-pump bonded 'back-to-back' with 4-mil (102 μm) spacing, an induced pumping pressure of 287 Pa has been achieved with 120 volts.

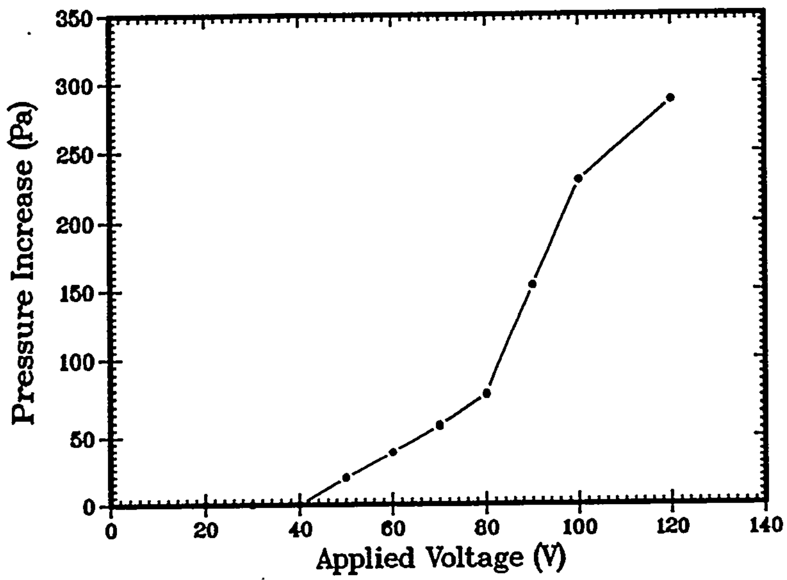

Figure 6. Induced Pressure as a Function of Applied Voltage. (EHD pump: 'back-to-back', 4-mil grid size, spacing, & distance.)

6. ACKNOWLEDGMENTS

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