INK JET FABRICATED NANOPARTICLE MEMS

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ABSTRACT

This paper presents a novel three-step process utilizing an ink jet print head to fabricate active MEMS devices. Both an in-plane and vertical thermal actuator with 100 µm lines are demonstrated, as well as a printed electrostatic linear drive motor. Fabrication of the devices is achieved by selective ink jet deposition of nanoparticles onto a surface of either glass or plastic. The ink jet printing of nanoparticles is shown to be a viable technology for building MEMS structures which consist of a large number of layers (>100), a diverse material set (metals, semiconductors, and insulators) and which have the ability to cover large areas. Such an approach represents a potential route to a complete desktop semiconductor fab.

INTRODUCTION

Over the past 25 years silicon wafer MEMS technology has demonstrated the ability to fabricate physical actuators that generate motion electrothermally or electrostatically. [1,2]. To date however such structures have been limited to not more than five layers of structure and have been constrained to placing machines on surfaces no larger than current wafer dimensions.

Another emerging fabrication technology, ink jet printing, has demonstrated the capability of building detailed three-dimensional structures out of wax, plastics, metal powders, and eutectic solders [3]. Ink jet printing can also cover areas in excess of 20”x20”. To date the role of ink jet has been limited in the material set which may be deposited and has been restricted to building static structures. In this report we present the first demonstration of the use of ink jet to build an active, functional structure.

NANOPARTICLE MEMS

Recently our group has shown that nanoparticles can be very useful for building electronic structure, and in fact have demonstrated the highest mobility transistors ever fabricated by printing [4]. In this paper we use nanoparticles to build another type of structure which is traditionally made in a silicon fab, MEMS.

Nanoparticles are small clusters of metal, semiconductor, or insulator, typically consisting of 10’s to 1000’s of atoms with particle sizes of several nanometers. In the context of ink jet fabrication, the most striking feature of nanoparticles of this size is a vastly suppressed melting point, which can be as low as 1000 °C below the bulk melting point [5]. We refer to this reduced melting point effect as nanotectic. In this paper we introduce the idea of nanotectonics, the construction of functional structures using nanotectic materials. By using such materials we can fabricate structures at low temperature which, once fabricated, can withstand subsequent exposure to high heat and are essentially equivalent in terms of structure and morphology to what is traditionally created in a vacuum.

PIEZO INK JET DEPOSITION

To pattern these materials, we’ve employed a piezo-electric ink jet system. Traditionally used to deposit pigmented inks on to paper, and more recently to build three-dimensional structures, we use ink jet printing to selectively deposit nanoparticles to construct MEMS devices. Ink jet heads commercially available already have the capability to expel droplets small enough to enable 20 µm feature sizes.

The ink jet head used to fabricate the MEMS reported, manufactured by Hitachi Koki, expels tiny droplets of ink consisting of silver nanoparticles suspended in α-terpineol. Expulsion is achieved by capacitively charging a piezo crystal, which elongates, pressing on a membrane of the ink chamber. The elevated pressure in the chamber forces the fluid out of the orifice with enough energy to overcome hydrostatic surface tension, ejecting the ink from the orifice in the form of a droplet. Droplet volume is 80 to 100 picoliters. Each ejected droplet is deposited on the substrate 1 mm to 2 mm away. Capillary action refills the emptied orifice.

The ink jet head can be heated or cooled to change the viscosity of the ink to be compatible with the requirements of the head. A 3-axis, computer controlled gantry system positions the head in 3-space. A function generator is used to generate a 100 Hz to 8 kHz repeating pulse to continuously drive a single ink jet nozzle and the computer controls whether the signal reaches the ink jet head depending on the program.

Feature size can be reduced and repeatability increased if the substrate is heated. A heated substrate causes the solvent in the ink to rapidly evaporate before it has a chance to substantially wet the surface.

The released thermal actuator is printed with the process shown in Figure 1. A draw down bar spreads a sacrificial etch release material over a portion of the substrate. Subsequently, the ink jet print head deposits all of the structural material. Some of the deposited material adheres directly to the substrate and the cantilever portion is deposited on top of the release layer. The printed device is heated in a furnace at 300 °C for 10-30 minutes to sinter and fuse the nanoparticles, as well as to remove organic capping groups. Then the whole device is lightly sonicated in an appropriate solvent to etch the release layer, leaving just the cantilever, adhered at its base. Release has been achieved using PMMA, polyimides, and photoresists. In addition to the draw down method indicated in Figure 1, we have demonstrated ink jet deposition of both photoresist and polyimide.

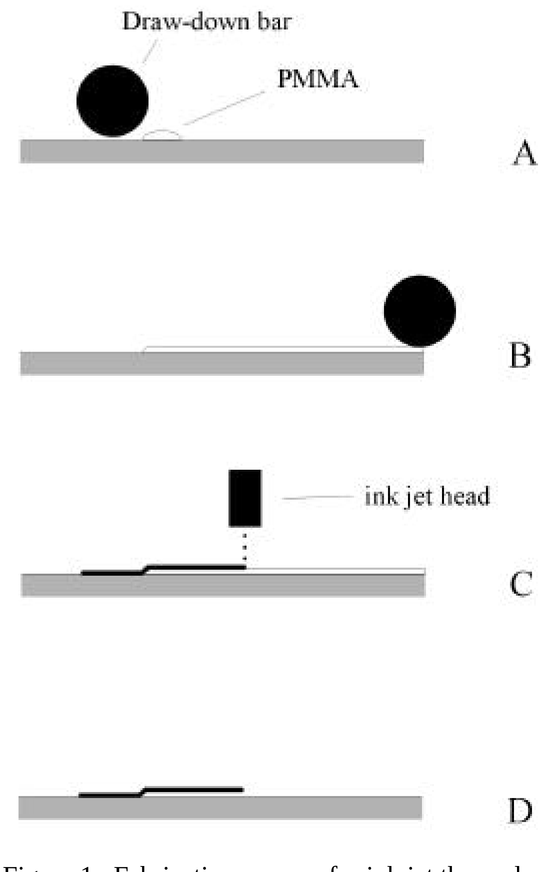

Figure 1: Fabrication process for ink jet thermal actuator. (A) A liquid consisting of PMMA dissolved in acetone is deposited on the substrate. (B) Draw down bar suspended above substrate spreads sacrificial release layer. (C) Ink jet head deposits nanoparticles, then deposit is sintered at 300 C. (D) Sonication in acetone dissolves away sacrificial PMMA.

In analogy to the silicon MEMS process, the sacrificial release layer is patterned, then a structural layer is patterned, and then the sacrificial layer is etched away leaving the structural layer separated from the substrate. The sacrificial release step has as its analog the CVD/etch oxide process and depositing nanoparticles is analogous to the CVD/etch polysilicon deposit. In contrast to silicon fabrication techniques, however, the structural material and the release material are deposited in a fully additive process described entirely by instructions to a computer, allowing rapid iteration. Further, ink jet technology can deposit a substantial range of materials, from metals to semiconductors to insulators. Lastly, all processing for the devices presented in this report was carried out at 300 °C or below, allowing us to build MEMS structures on flexible plastic substrates such as polyimide film.

RESULTS

Two forms of thermal actuator are presented, as well as a linear drive motor. All were printed using roughly the above technique, though details pertinent to each device are given.

Figure 2 is a printed linear drive motor. It consists of a repeating pattern of three inter-digitated, conducting lines, each on a separate bus, printed on a 50 µm sheet of polyimide plastic. Two are printed on one side, the third is printed on the other side. Small 250 µm dielectric balls can be shuttled across its surface by selectively giving each trace a 100 volt charge.

The images shown are of a drive motor that was printed onto a plastic substrate held at room temperature. Line width is 200 µm. Each layer was printed, and a hot-air gun was used to evaporate the wet α-terpineol before the subsequent layer was added. The device is printed with five layers. Later operational devices were printed with only one pass onto a heated substrate. The heated substrate caused a reduction line width from 200 µm to 80 µm. Sinter time for both devices was 10 minutes at 300 C.

Figure 3 is a printed thermal actuator that employed a PMMA sacrificial release layer. The substrate was a glass slide. The release layer was patterned by covering a portion of the substrate with a solution of poly-(methyl-methacrylate), or PMMA, in acetone. The PMMA was dissolved in acetone and much of the acetone was subsequently allowed to evaporate away, leaving a viscous solution. A capillary tube was used to deposit a droplet of the solution onto the substrate, and a round draw-down bar was immediately pulled over the droplet, spreading the material as evenly as possible over the surface. The draw down bar was suspended 125 microns above the substrate. PMMA is not an ideal release layer because the nanoparticle ink solvent can

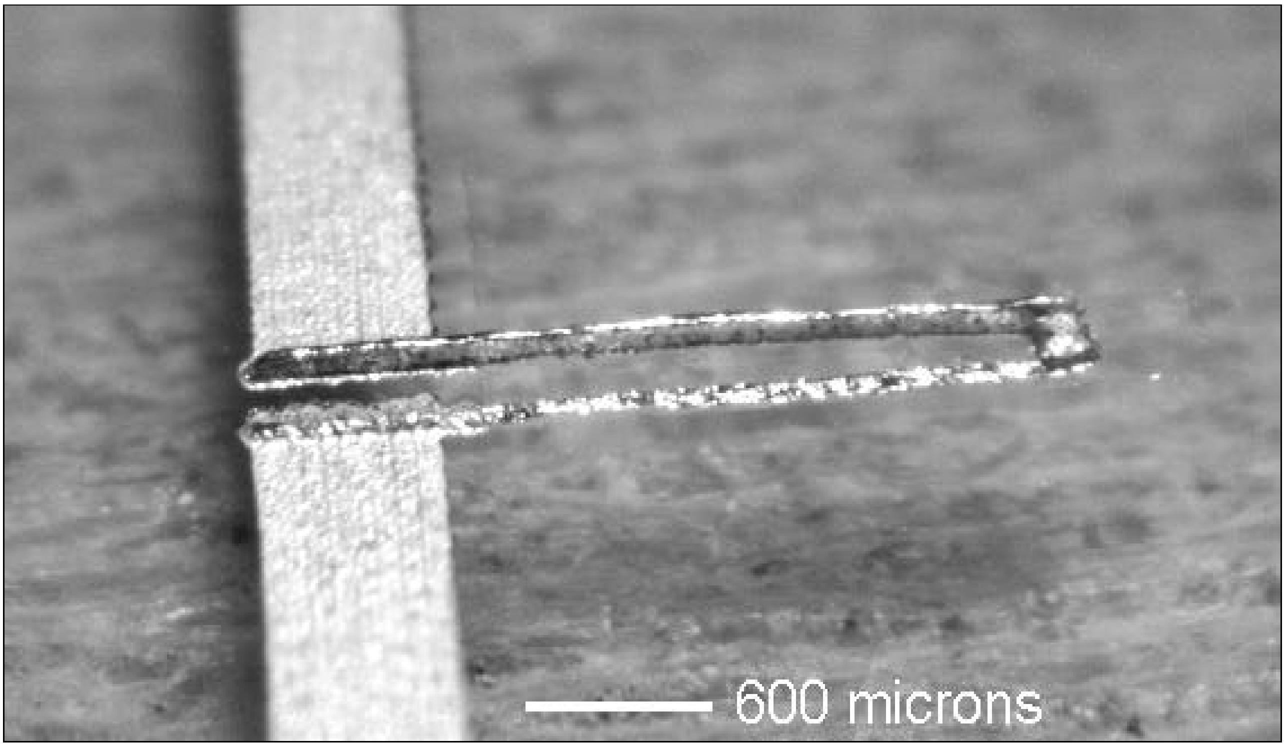

Figure 3: All-printed electrothermal actuator fabricated by ink jet. The far cantilever has three times the cross-sectional area as the near cantilever.

dissolve the deposited PMMA, leaking through to the substrate and adhering.

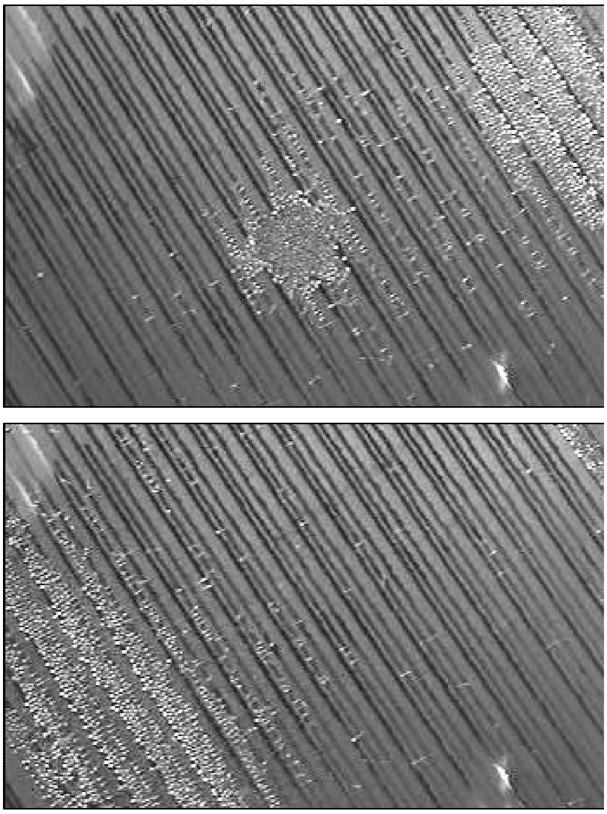

Figure 2: All printed linear drive motor shuttling 250µ dielectric balls.

While ink jetting the hotplate was heated to 200 °C. Though individual droplets were roughly 80 µm across, feature size of the device is roughly 100 µm because of drop placement variations. The printing process consisted of printing a layer and pausing for 3 seconds between layers to evaporate off the solvent. The thick half of the actuator consists of 120 passes, the thin layer 40 passes. Each layer consists of droplets separated just enough that no droplet touches another droplet on its layer. The contact pads at the top and bottom of the photograph consist of 16 layers each.

The printed device demonstrated a 200 µm travel at the tip of the 3 mm cantilever. Power usage was 25 mW. A frequency of 4 Hz was achieved.

Figure 4 is a thermal actuator printed vertically with 400 layers. The substrate, also a glass slide, was heated to 275 °C. Each layer consists of several droplets deposited in rapid succession in combination with a pause for solvent burn off. The thicker half consists of three columns stuck together. As the device was built upward, heat flow upward through cantilever arms reduced, so at the top the solvent in each layer did not fully evaporate off before the next layer was added. As desired, eventually, the “mushrooming” effect caused the two towers to join at the top. The total height of the

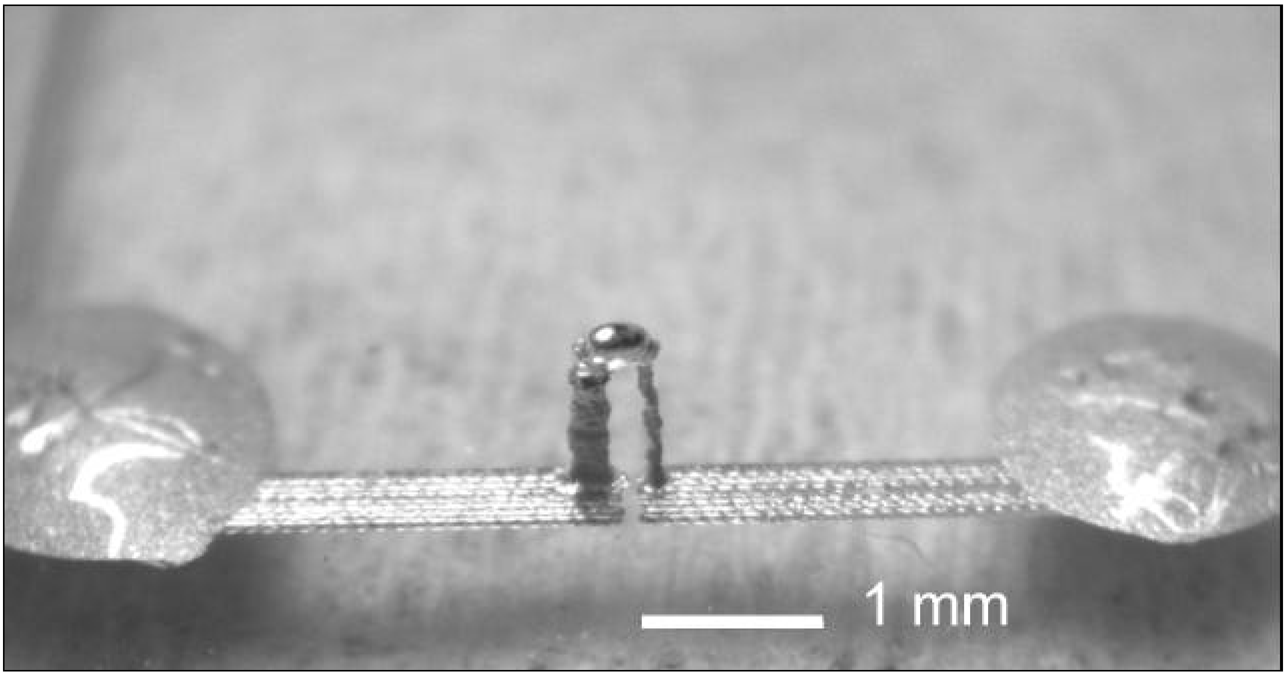

Figure 4: Vertical electrothermal actuator.

device is 1000 μm. The device was sintered at 300 °C for 30 minutes.

CONCLUSION

Ink jet has been demonstrated as a viable technology to be used for building MEMS type structures. Its benefits as a potential technology for micron scale fabrication are many:

1. It can deposit a range of nanoparticle materials including conductors, semiconductors and insulators in addition to polymers.
2. There is no inherent limit to the number of layers that can be deposited.
3. Ink jet can be used over large areas and even curved and flexible surfaces.
4. The low process temperature of 300 C allows devices to be built even on plastic.
5. Finally ink jet nanoparticle MEMS is a promising route to creating a true desktop semiconductor fab.

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REFERENCES

[1] J. H. Comtois, V. M. Bright, M. Phipps. Proc. SPIE, vol. 2642, pp. 10-21, 1995.
[2] J. Jonsman, O. Sigmund, S. Bouwstra, MEMS '99, pp. 588-593.
[3] E. P. Muntz, M. E. Orme, and G. C. Pham-Van-Diep with R. Godin, 1997 International Symposium on Microelectronics, pp. 671-680.
[4] B. A. Ridley, B. Nivi, and J. M. Jacobson. Science, Vol. 286, pp 746-749, 1999.
[5] Ph. Buffat, J.-P. Borel, Phys. Rev. A, vol. 13, p. 2287, 1976.