

Modification of Micronozzle Surfaces Using Fluorinated Polymeric Nanofilms for Enhanced Dispensing of Polar and Nonpolar Fluids

J. D. Jeyaprakash S. Samuel,^{†,‡} Reinhard Steger,[§] Gerhard Birkle,[§] Roland Zengerle,[§] Peter Koltay,[§] and Jürgen Rühle^{*,†}

Laboratory for MEMS Applications and Laboratory for Chemistry and Physics of Interfaces, Institute for Microsystems Technology, University of Freiburg, 79110 Freiburg, Germany

In this work, we report on the surface modification of a micronozzle surface to enhance fluid dispensing in the nanoliter range. Unmodified dispensing chips usually suffer from lateral wetting of the nozzle surfaces by low surface tension liquids resulting in poor control of the volume of the dispensed fluid. Covalent attachment of a fluorinated acrylate polymer to the outer surface of the micronozzle using a novel UV irradiation process helps to overcome capillary and adhesive forces and results in an enhancement of the control on fluid dispensing in the nanoliter range. The modified nozzles have been tested with a variety of fluids having a wide range of surface tensions. The surface modification allows precise control of the dispensing of nanoliter droplets with a high degree of reproducibility.

The past few years have seen a tremendous growth in the design and fabrication of microdevices used for the delivery of biochemical fluids in the microliter and nanoliter ranges.^{1–5} Typical applications are in the area of combinatorial synthesis of new pharmaceutically active compounds, in high-throughput screening^{6,7} of large libraries of new compounds, or in the fabrication of microarrays for genomic or diagnostic applications in the biotech industry. In all these applications, a wide spectrum of fluids with varying viscosities and surface tensions have to be handled.

The dispensing of liquid volumes in the microliter range, sometimes even down to 500 nL, can be easily carried out by handheld pipets or pipetting workstations. They operate with pipet

tips that are inserted into the liquid to aspirate and to dispense the reagents. For even smaller volumes, capillary and adhesive forces at the pipet tips result in relatively large volume errors and also increase the risk of cross-contamination. Therefore, during the past decade, many groups developed dosing systems that dispense the liquid as free-flying droplets or as jets (see refs 8–17 for examples). As all ink-jet printers use such processes, contact-free dispensers are currently also of great commercial importance. For all noncontact dispensers, the droplet-forming process at the nozzle is a critical part of the system (Figure 1a). This process is strongly influenced by the surface tension, the viscosity of the liquid to be dispensed, and the viscosity of the liquid to be dispensed as well as by the surface energy of the outer nozzle surface. Prevention of wetting of the liquid on the outer nozzle surface is an absolute prerequisite for all nanoliter or picoliter dispensing devices for several reasons: If the outer surface does not strongly prevent wetting, even a small hydrostatic pressure difference between the reservoir and the nozzle will cause the liquid to flow out of the nozzle and cause it to slowly spread over the entire outer surface of the dosing chip. This situation is indeed typical for nozzles micromachined into silicon, as it has a relatively high surface energy and is accordingly easily wetted by low surface tension liquids. This eventually leads to a leaking of the micronozzle. An example for a case in which such a problem occurs is shown in Figure 2 for the NanoJet dispensing device, where dimethyl sulfoxide (DMSO) was used as the dispensing

* To whom correspondence should be addressed. E-mail: ruehe@imtek.uni-freiburg.de.

[†] Laboratory for Chemistry and Physics of Interfaces.

[‡] Present address: IBM Almaden Research Center, 650 Harry Rd., San Jose, CA 95120.

[§] Laboratory for MEMS Applications.

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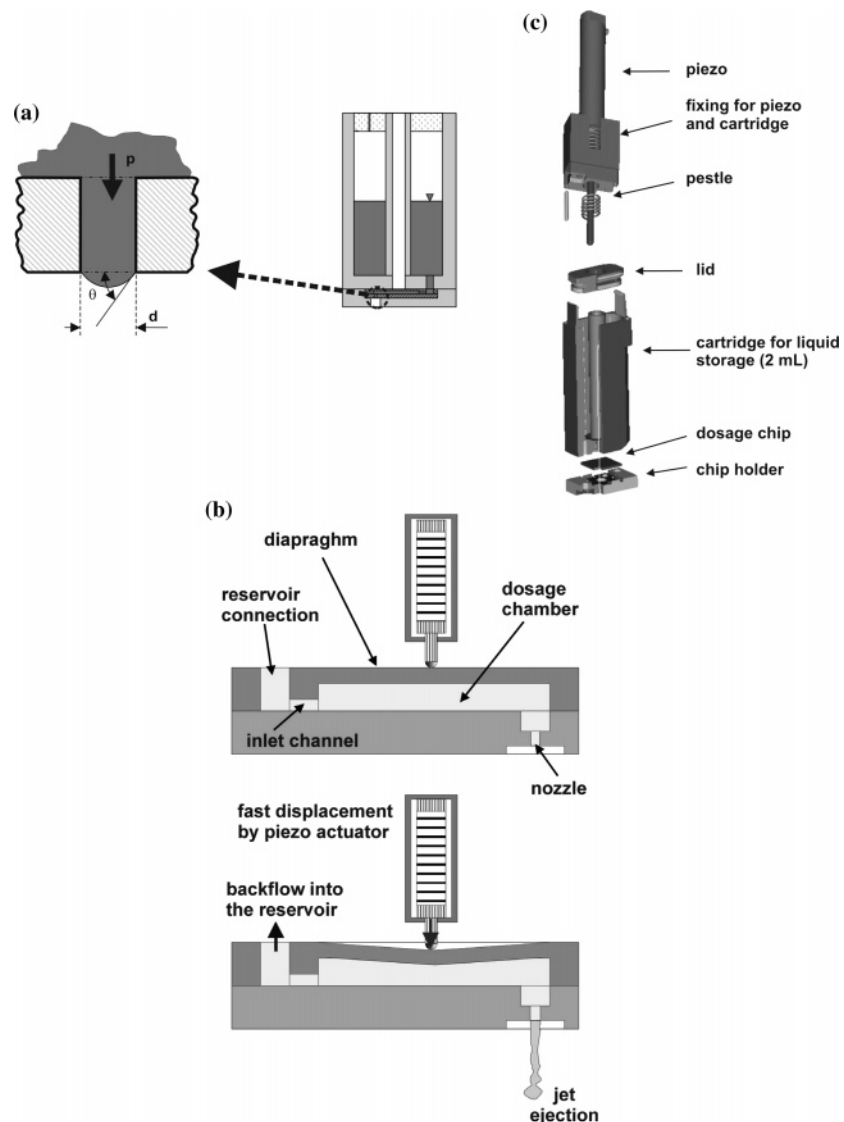


Figure 1. (a) Schematic description of the dispensing process at the nozzle orifice of a NanoJet chip and a liquid cartridge container (θ , contact angle of the fluid at the micronozzle interface; d , diameter of the micronozzle). (b) Cross section of the dosage chip. (c) Sketch of a single channel of the dispensing device.

fluid. It can be easily seen that, even without any hydrostatic pressure applied, the liquid flows out of the nozzle and spreads on the whole chip surface.

A second problem is that wetting of the nozzle also increases the kinetic energy needed for the droplet to break away from the surface. This decreases the ability to control the size of the drops that are dispensed by the chip. Last but not least, any wetting of the outer nozzle surface enhances the probability that the drop or jet does not break off in all locations simultaneously. This will cause the drop to leave the chip not exactly perpendicular to its surface and eventually cause it to hit the substrate off target.

Two different strategies have been proposed to circumvent wetting-imposed limitations on dispensing small volumes with micronozzles. The first is a geometrical solution, in which the nozzle is designed in such a way that the liquid is not able to wet the surface outside the nozzle. Different approaches for such a solution have been tested.^{13,17} In one example, a tubelike nozzle as shown in Figure 3 is generated, in which the nozzle outlet is turned $\sim 180^\circ$ against the gravitational force. In this case, a liquid

cannot wet the shell surface of the tube, because the additional pull on the liquid by the gravitational force does not allow the meniscus to reach this surface. Although these approaches show a good behavior with several liquids, problems start to arise when organic solutions with surface tensions below 30 mN/m are used. Tests with different tubelike nozzles as depicted in Figure 3 have shown that wetting of the complete nozzle area occurs if liquids such as 2-propanol or methanol are used. In these cases, the wetting happens not during the filling of the nozzle but during the droplet ejection process when the droplet breaks up and a small portion of the liquid is sucked back, which cannot re-enter the nozzle.

The second approach involves the modification of the area around the micronozzle tip making it hydrophobic/solvophobic through the deposition of low surface energy coatings. To this, frequently fluorinated compounds are attached to the chip surfaces. However, most of the processes used to generate low-energy surfaces use cumbersome techniques such as plasma polymerization of fluorinated monomers, argon plasma sputtering

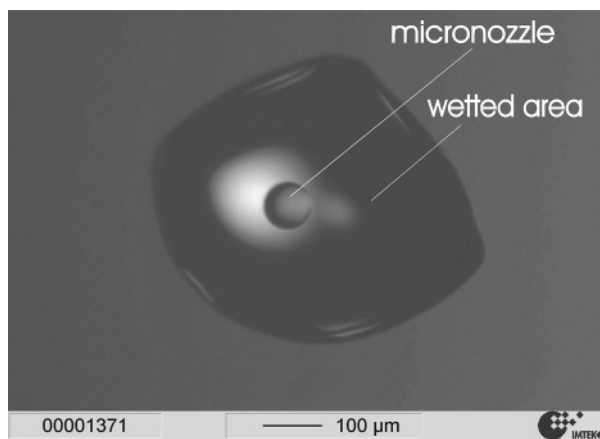


Figure 2. Optical micrograph of an unmodified NanoJet chip after dispensing of DMSO. Strong lateral wetting can be seen around the nozzle surface.

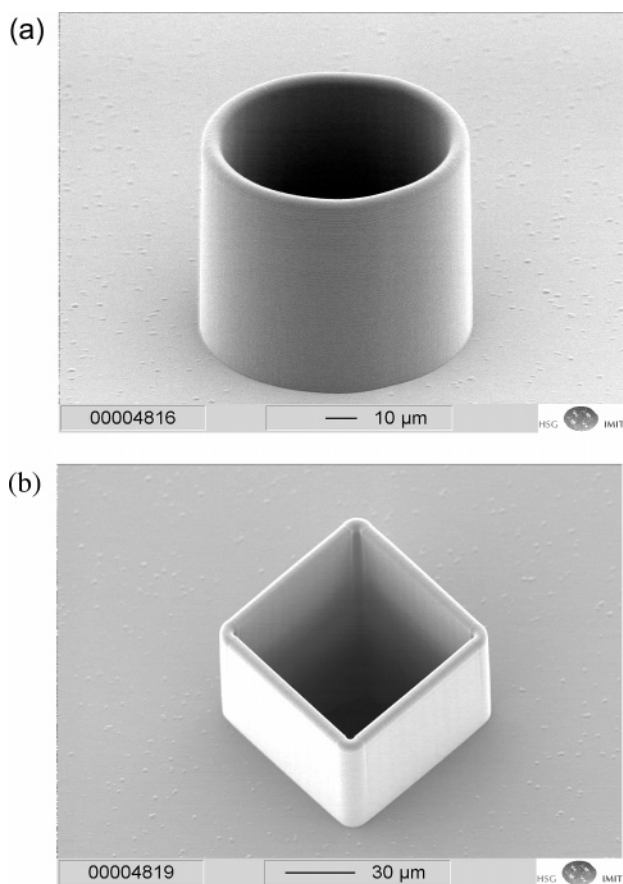


Figure 3. SEM images of two different tubelike nozzle designs.

of fluoropolymers, pulsed laser deposition, and others.^{18–25} Such processes, however, require harsh conditions, which could lead

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to damage of the substrates. Furthermore, the adhesion between the coating and the chip surface is usually rather weak, so that the long-term stability of the surface modification poses a problem. In addition to this, a sufficient spatial control of the deposition of the fluorinated material is difficult to achieve with most of the techniques described so far.

We report in this work on the photochemical attachment of fluorinated polymers to the outer surfaces of micronozzles through a simple, photochemical process yielding monomolecular layers of the polymers covalently attached to the nozzle surfaces. The preparation of the layers and the performance of devices containing such surface-modified micronozzles are described.

EXPERIMENTAL SECTION

Design and Fabrication of the NanoJet Dispensing Device.

It has been already demonstrated that the dispensing process called the NanoJet method or NanoJet principle in contrast to drop-on-demand or syringe solenoid methods allows highly accurate dispensing of liquids independent of their viscosity in a range from 1 to 100 mPa·s.²⁶ The system allows a variable adjustment of the dispensing volume by the actuation signal of a piezoactuator. The heart of the device consists of a microfluidic dosage chip micromachined with standard dry etching technology. Typically the chip is realized as a two-layer bond of silicon or silicon/Pyrex. The key features of the dosage chip are an inlet channel for liquid supply, a dosage chamber bounded on one side by a silicon diaphragm, and an outlet channel with a nozzle for liquid ejection.

These key features can be observed in Figure 1b, where the cross section of a dosage chip is sketched, which has been optimized for a linear arrangement as shown in Figure 1c. The device shown here has a small footprint of $9\ \mu\text{m} \times 18\ \mu\text{m}$, which makes it possible to form very dense arrays out of individual dispensers.

Due to capillary forces, the microfluidic chip is self-priming. Thus, by mounting the dosage chip onto the cartridge containing the liquid as shown in Figure 1c, the whole chip is readily and completely filled with liquid.

Dispensing Process. The NanoJet principle is based on a very fast and defined mechanical displacement of liquid out of the dosage chamber. This is achieved in this system by a piezostack actuator. The stroke of the piezostack actuator can be controlled very precisely leading to a well-defined volume displacement of the diaphragm, forming the top of the dosage chamber. Due to the displacement, a defined liquid volume is forced out of the dosage chamber. The ratio of liquid forced out of the chamber via the nozzle compared to that pushed back into the reservoir is fixed by the ratio of the flow resistances of both channels. Although the flow resistance of every single flow channel depends very much on the liquid properties such as viscosity, surface tension, etc., the ratio of both flow resistances does not. Therefore, the quantity of liquid delivered via the nozzle is a well-defined, fixed fraction of the volume displacement of the diaphragm. In a first approximation, this fraction does not depend on the liquid viscosity in a wide range and exhibits a good linear correlation to the displacement.

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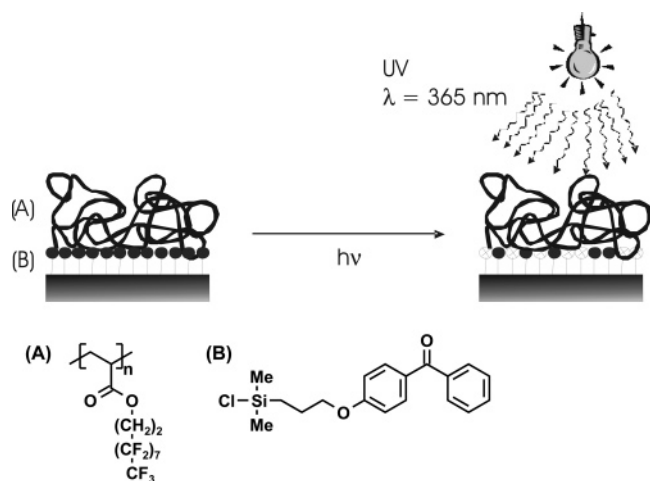


Figure 4. Schematic description of the photochemical attachment of a fluoropolymer onto micronozzle surfaces.

Surface Modification of the Dosing Chip. A schematic description of the surface modification of the dosing chip is shown in Figure 4. The surface of the chip is initially modified with a self-assembled monolayer of a monochlorosilane bearing a benzophenone group at the other end as reported earlier.²⁷ The chemical structure of the compound is shown in Figure 4 a. The monochlorosilane moiety reacts with the surface hydroxyl groups of the oxide layer and results in the formation of a well-defined monolayer containing benzophenone groups.

1*H*,1*H*,2*H*,2*H*-Perfluorodecyl acrylate polymer was synthesized at 60 °C by free radical polymerization using bulk monomer and 0.5 mol % AIBN as initiator. Prior to polymerization, the monomer was degassed through repeated freeze–thaw cycles to remove oxygen traces. By varying the initiator concentration and concentration of the monomer, the molecular weight of the polymers can be easily controlled.²⁸ After a polymerization time of 3 h, the resulting polymer was purified through repeated dissolution/precipitation cycles using Freon and methanol as solvent and nonsolvent, respectively, and dried under vacuum. Some fraction of the polymer was then dissolved again in Freon and dip coated on the micronozzle surface modified with the benzophenone silane. The thicknesses of the thus obtained films were 40–50 nm according to ellipsometry measurements performed on the same substrates without nozzles. The micronozzle chip was then exposed to UV radiation having a wavelength of 360 nm for 60 min using a high-pressure mercury lamp.

Chemicals. 1*H*,1*H*,2*H*,2*H*-Perfluorodecyl acrylate (Aldrich, 97%) was purified chromatographically over neutral AlO₃, distilled under vacuum from copper(I) chloride, and stored at –30 °C. Toluene was distilled from sodium after refluxing it overnight. Benzophenone was used as an indicator. Triethylamine was dried by distillation from CaH₂, and 1,1,2-trichlorotrifluoroethane (Freon, Fluka) was used as received. Dimethylchlorosilane was purified by distillation. The other chemicals were used as received.

Instrumentation. Ellipsometric measurements were performed on a DRE-XO2 C ellipsometer operating with a 638.2-nm He/Ne laser at 70° incident angle by assuming that the refractive

index of the fluoropolymers film is the same as that of the bulk material ($n = 1.337$). Contact angle measurements were performed on the modified chip using a contact angle goniometer (Data Physics Instruments). Stroboscopic images of the dispensing of the fluids were obtained using a Mococon RT Videostroboscope together with a stereolens Leica MZ 16 at 4× magnification. Microscopic images were obtained using a Zeiss Axioshot microscope at 10× magnification coupled with a digital camera, Kontron Electronic ProgRes 3008. Gravimetric measurements of the dispensed fluids were performed using a Sartorius SC2 balance, which has an accuracy range of 0.1 μg. Fluorescence measurements were performed using a Bioanalyzer from LaVision Biotec instrument using a 1-mK CY3 40-mer fluorescent marker in 3× SSC buffer with 1 M betaine concentration.

RESULTS AND DISCUSSION

Surface Modification Using Fluoropolymer. Detailed studies of the kinetics of the photochemical processes have been reported elsewhere.²⁸ During the irradiation, the benzophenone undergoes an n, π^* transition and abstracts a hydrogen atom from the fluoropolymer followed by a radical–radical coupling process. This leads to a covalent attachment of the polymer to the benzophenone molecule, which in turn is chemically bound to the substrate surface (Figure 4). After completion of the photo-reaction, the unbound polymer is removed by solvent extraction. The thickness of films obtained by the photoimmobilization strategies described here generally scales with the square root of the molecular weight of the polymer. For the polymer synthesized here, a film thickness of 12 nm was obtained. Additionally, it is also possible to irradiate the substrates at 260 nm by making use of the π, π^* transition to generate the biradicaloid intermediate. In this case, very short irradiation times ($\tau < 120$ s) can be employed.

It should be noted that only molecules in direct contact with the surface can be covalently attached to the substrate. Accordingly, the thickness and homogeneity of the initially deposited film do not matter as long as the film thickness in all areas is higher than a critical value of roughly 40–50 nm (depending on the molecular weight of the polymer). If this is the case, the thickness of the final surface-attached monolayer is completely independent of the thickness of the initially deposited film. This situation is very favorable as it allows for the application of many different techniques of film deposition such as dip coating, painting, and spray coating to name just a few examples. Use of dip coating and photoattachment enables a precise coating of the area to be modified, as the only areas containing the benzophenone silane bind the polymer.

Contact angle measurements of various test liquids on one film obtained by this method are shown in Table 1. It is evident that even quite nonpolar test liquids such as hexadecane show rather high contact angles on the fluorinated surfaces and droplets of such liquids do not spread on the thus modified silicon surfaces, so the adhesion of the droplets to the substrate is relatively weak.

Dispensing Quality of the Surface-Modified Dosing Chips. Dispensing low surface tension liquids on unmodified micronozzles is severely distorted due to lateral wetting of the fluid around the micronozzle (Figure 2). Analysis concerning the accuracy of the volume of liquid dispensed by the micronozzle

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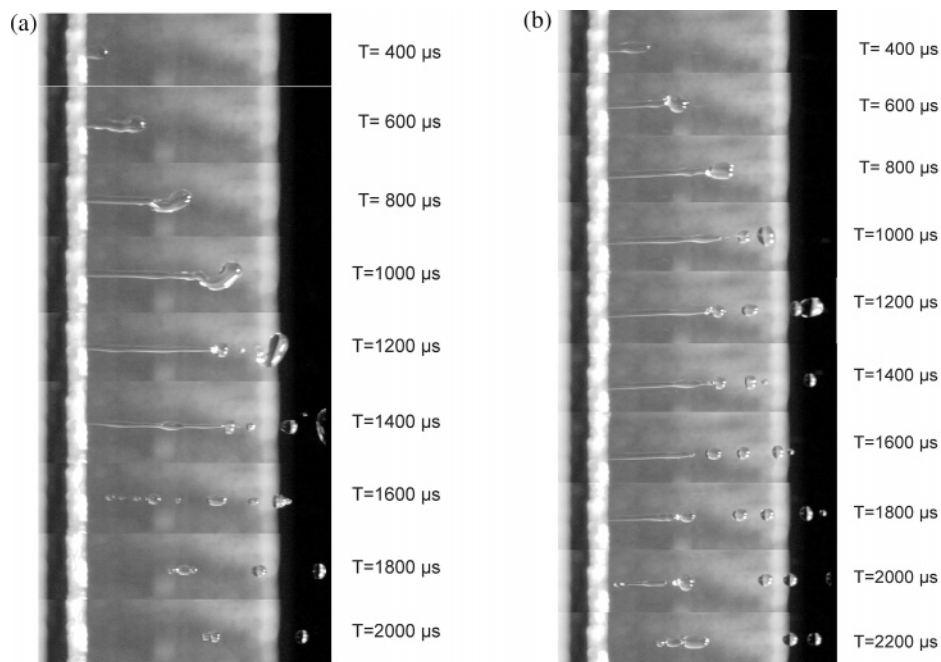


Figure 5. Stroboscopic images of the ejection of a liquid jet with (a) 2-propanol and (b) distilled water.

Table 1. Contact Angle of Various Test Liquids on a Fluoropolymer Modified Silicon Surfaces

test liquid	surface tension at 25 °C (mN/m) ²⁹	contact angle (deg)
dodecane	25.4	69
cyclohexane	24.7	72
hexadecane	27.1	78
methanol	22.1	80
ethylene glycol	48.0	100
water	72.0	120

was carried out by weighing the mass of the dispensed fluid for each stroke. The nozzle diameter in this case was 80 μm and a 30- μm stroke with an ejection speed of 18 $\mu\text{m}/\text{ms}$ was employed. A plot of the volume of the dispensed fluid as a function of the number of dosings for an unmodified chip is shown in Figure 6. In this case, 2-propanol was used as test liquid. It can be clearly seen that the volume of the 2-propanol drops fluctuates randomly from a minimum value of 15.5 nL to a maximum value of 49.2 nL. The average value was 32.6 nL with a standard deviation of 4.9 nL. Accordingly, the largest drops are more than a factor of 3 larger in size than the smallest ones. This deviation arises from the lateral wetting of the dosing chip caused by the low surface tension fluid resulting in uneven drop sizes.

The dosing chips modified with the fluoropolymer show a quite different dispensing behavior compared to the unmodified ones. Figure 5 shows the jet ejection of water and 2-propanol from dosing chips modified with the fluoropolymers as a sequence of different stroboscopic pictures. It is clearly evident from this figure that both 2-propanol and water having surface tensions of 21 and 72 mN/m,²⁹ respectively, can be dispensed in the form of a controlled jet without any lateral wetting. In both cases, the lower surface tension of the modified chips facilitates the complete break-off of both the dispensing fluids thus preventing them from

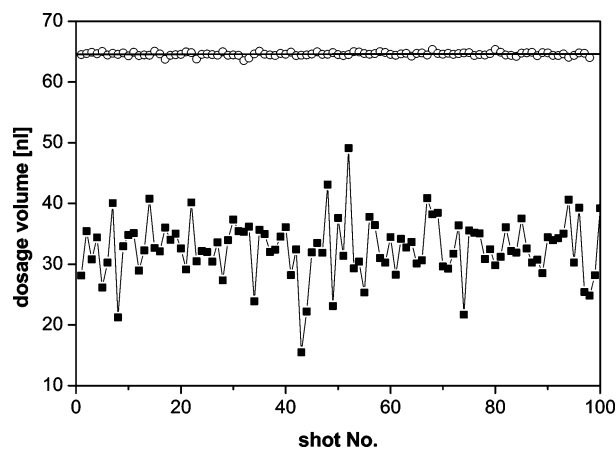


Figure 6. Volume of ejected jet of 2-propanol from an unmodified micronozzle (■) and a surface-modified micronozzle (○) against shot number. The solid line indicates the theoretically expected dosage volume for a micronozzle of 80- μm diameter using a 30- μm stroke and ejection speed of 18 $\mu\text{m}/\text{ms}$.

spreading on the surface. This can be seen especially in the last of the stroboscopic images, where in both cases, no deposit is formed at the tip of the nozzle at the end of the dispensing process. When a direct comparison of the different situations depicted in Figure 5 is made, it should be taken into account that the material with the smaller surface tension breaks off more easily, which can be seen by the time lag of 200 μs between the fluid ejections of the different liquids. Further analysis concerning the accuracy of the ejected volume was carried out gravimetrically for a micronozzle similar to that used in Figure 6, but modified with the fluoropolymer. The nozzle diameter was also 80 μm , and the dispensing was carried out under similar conditions. A plot of dispensing volume against dosing number for a chip modified with a fluoropolymer is shown in Figure 6. Surface modification of the dosing chip with the fluoropolymer enhances the tearoff of the liquid jet from the nozzle orifice. This results in much smaller

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fluctuations of the dispensing volume. The average value was 64.6 ± 1.0 nL and with a standard deviation of 0.3. This compares favorably to the average value of the standard deviation of 4.9 for unmodified chips. Apart from narrowing the fluctuations in dispensing volume, the volume of drops dispensed by the modified chips was closer to that expected for a nozzle with the given dimensions. Whereas drops dispensed by unmodified chips were roughly only half of the volume expected from membrane displacement due to lateral wetting, chips with modified nozzles were much closer to expectations.

Surface modification with the fluoropolymer also enables a precise control of the volume of the dispensed fluid by changing the stroke of the piezoactuator. The ejected volume was measured as a function of the piezostroke at an ejection speed of $18 \mu\text{m}/\text{ms}$ and a refilling speed of $0.05 \mu\text{m}/\text{ms}$. Methanol was chosen as the test liquid. By varying the stroke of the piezoactuator, the volume of the dispensed fluid could be varied precisely from 2 to 42 nL. The standard deviation in these experiments was $\sigma = 0.46$ (for $N = 16$ measurements) and the correlation coefficient was $R = 0.9994$. To visualize the uniformity of the ejected droplets, a fluorescent dye (Cy-3) dissolved in a SSC buffer was dispensed and the ejected droplets were imaged under a fluorescence microscope (data not shown).

In addition to the issue of drop volume control, it is also interesting to note that modification of the device surfaces with the fluoropolymer layer allows one to use nozzles with larger diameters without any problems. If in conventional dispensing chips the nozzle size (typically between 40 and $120 \mu\text{m}$) is increased, the capillary pressure decreases. A lower capillary pressure, however, makes problems related to wetting even worse. Modification of the surface with the fluoropolymers, however, helps to overcome such problems and enable the use of micron-

nozzles with diameters larger than $40 \mu\text{m}$, which can deliver higher volume per piezostroke. Thus, the volume range accessible with the same nozzle design is strongly expanded.

CONCLUSIONS

In this work, controlled fluid dispensing of low and high surface tension liquids in the nanoliter range has been successfully demonstrated. This is achieved through chemically anchoring strongly solvent repellent polymeric nanofilms onto micronozzle surfaces through a simple photochemical process. In this process, fluorinated polymers become covalently attached to the outer nozzle surfaces. The surface modification step helps to overcome capillary and adhesive forces, which otherwise cause lateral wetting around the nozzle orifice. By preventing wetting of the nozzle surface, the surface modification process eliminates fluctuations in the dispensed volume and allows delivery of nanoliter droplets, even of low surface tension liquids, in a highly reproducible manner. As a consequence, the dispensing properties of such devices are strongly improved compared to unmodified micronozzles. The described surface modification also opens the door to deliver higher volume per piezostroke and the use of micronozzles with relatively large diameters, thus widening the parameter range obtainable with one nozzle design.

ACKNOWLEDGMENT

Funding of the presented work by the Company Morphochem AG, Munich is gratefully acknowledged.

Received for review May 19, 2005. Accepted June 23, 2005.

AC050878E