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(54) Title: MONOLITHIC MULTINOZZLE EMITTERS FOR NANOELECTROSPRAY MASS SPECTROMETRY

(57) Abstract: Novel and significantly simplified procedures for fabrication of fully integrated nanoelectrospray emitters have been described. For nanofabricated monolithic multinozzle emitters (NM^2 emitters), a bottom up approach using silicon nanowires on a silicon sliver is used. For microfabricated monolithic multinozzle emitters (M^3 emitters), a top down approach using MEMS techniques on silicon wafers is used. The emitters have performance comparable to that of commercially-available silica capillary emitters for nanoelectrospray mass spectrometry.

MONOLITHIC MULTINOZZLE EMITTERS
FOR NANOELECTROSPRAY MASS SPECTROMETRY

STATEMENT OF GOVERNMENTAL SUPPORT

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TECHNICAL FIELD

[0002] This invention relates generally to electrospray ionization emitters for mass spectrometry, and, more specifically, to methods for forming such emitters for nanoelectrospray mass spectrometry for proteomic and metabolomic applications.

BACKGROUND ART

[0003] Mass spectrometry measures the mass-to-charge ratio (m/z) of ions formed from analyte molecules. As shown in Figure 1, mass spectrometers have three principal components: an ion source, a mass analyzer and an ion detector. The function of the ionization source is to convert analyte molecules into gas phase ions. Electrospray ionization (ESI) is a technique used in mass spectrometry to produce ions. It is especially useful in producing ions from macromolecules because it overcomes the propensity of these molecules to fragment when ionized. The ions are accelerated under vacuum in an electric filed and separated by mass analyzers according to their m/z ratios. Exemplary mass analyzers include triple-quadrupole, time-of-flight (TOF), ion trap, quadrupole-TOF, and Fourier transform ion cyclotron resonance (FTICR) analyzers. As individual ions reach the detector, they are counted. During the last several years, technological developments in mass spectrometers have greatly improved the mass accuracy, resolution and sensitivity. However, there still remain great opportunities and challenges in mass spectrometry.

[0004] Proteomics and metabolomics as are generating new knowledge-bases for hypothesis-driven biochemical and bioimaging studies. Mass spectrometry has been the enabling technology for much of this research. Yet, the sensitivity and dynamic range have not been sufficient for all analyses. Thus far, Fourier transform ion cyclotron resonance mass spectrometry has achieved some of the best results – a detection limit of 10 zmole (*i.e.*, 6000 molecules) for tryptic peptides of bovine albumin and a dynamic range of at least 6 orders of magnitude. This sensitivity suffices for the detection of the most abundant proteins in a single mammalian cell. However, due to the huge dynamic range (10^6-10^9) of proteins in the cell, it still remains a challenge to detect many of the less abundant proteins, even those that are present in large amounts. Revolutionary innovations can help to achieve proteomics and metabolomics of single cells. Mass spectrometry analysis that uses a very small sample size and has excellent ionization efficiency and extremely high resolution, accuracy, and dynamic range would be useful for performing such analyses.

[0005] One dominant soft-ionization method that can ionize large biomolecules such as peptides and proteins without significant fragmentation is electrospray ionization (ESI). In ESI, a volatile liquid containing an analyte moves through a very thin, charged capillary. The liquid is dispersed into a mist of small charged droplets by applying a high electric potential between the capillary and a counter electrode. As the liquid evaporates, highly charged analyte molecules explode out from the droplets. The smaller the droplets, the larger the explosion. In general, for conventional electrospray, the smallest capillaries have an inner diameter of approximately 1 µm and generate droplet diameters in the range of 1-2 µm with a flow rate of 20-40 nanoliters per minute (nL/min).

[0006] At sufficiently low flow rate and concentration, there is on average less than one analyte molecule per droplet. Ionization efficiencies can approach 100% as the analyte is dispersed in very small, easily desolvated, charged droplets. This limit is reached only if the concentration is low enough. The abundance of sample ions created by ESI can reach a plateau at certain concentrations and does not increase beyond the plateau even with increased sample concentration. Thus there is a limited dynamic range, which can be a serious drawback. In a complex mixture this problem can be especially severe. This ion suppression effect, which seems to occur at flow rates in the range of 50 nL/min and higher and is effectively absent at flow rates below approximately 20 nL/min, can render less abundant ions undetectable. Further reduction in the droplet size can alleviate this problem, increasing both the dynamic range and sensitivity of mass spectrometry.

[0007] In order to achieve lower flow rates, in the range of picoliters per minute (pL/min) or less, much smaller capillaries with sub-micron inner-diameters are needed. But there are difficulties associated with fabrication of such small capillaries, and there can be problems with increased back pressures from such extremely small channels. In addition, very small capillaries can lead to low throughput because of the need for careful and tedious alignment in the mass spectrometer.

[0008] There have been efforts to fabricate ESI emitters using polymeric materials, such as parylene (Licklider, L.; Wang, X. Q.; Desai, A.; Tai, Y. C.; Lee, T. D. *Anal. Chem.* **2000**, *72*, 367-375; Yang, Y. N.; Kameoka, J.; Wachs, T.; Henion, J. D.; Craighead, H. G. *Anal. Chem.* **2004**, *76*, 2568-2574), poly(dimethylsiloxane) (PDMS) (Kim, J. S.; Knapp, D. R. *J. Am. Soc. Mass Spectrom.* **2001**, *12*, 463-469), poly(methyl methacrylate) (PMMA) (Schilling, M.; Nigge, W.; Rudzinski, A.; Neyer, A.; Hergenroder, R. *Lab Chip* **2004**, *4*, 220-224), and negative photoresist SU-8 (Le Gac, S.; Arscott, S.;

Rolando, C. *Electrophoresis* **2003**, *24*, 3640-3647; Nordstrom, M.; Marie, R.; Calleja, M.; Boisen, A. *J. Micromech. Microeng.* **2004**, *14*, 1614-1617). However, inherent properties of these hydrophobic polymers, such as strong binding affinity to proteins and incompatibility with organic solvents, have limited their usefulness for electrospray applications.

[0009] There have also been efforts to fabricate ESI emitters using silicon-based materials, such as silicon nitride (Desai, A.; Tai, Y.; Davis, M. T.; Lee, T. D. International Conference on Solid State Sensors and Actuators (Transducers '97), Piscataway, NJ, **1997**, 927-930) and silicon/silica (Schultz, G. A.; Corso, T. N.; Prosser, S. J.; Zhang, S. *Anal. Chem.* **2000**, *72*, 4058-4063; Griss, P.; Melin, J.; Sjodahl, J.; Roeraade, J.; Stemme, G. *J. Micromech. Microeng.* **2002**, *12*, 682-687). In-plane silicon nitride emitter fabrication has failed due to intrinsic clogging problems arising from the etching of phosphosilicate glass between silicon nitride layers. Out-of-plane fabrication of silicon/silica has been limited critically because of the additional assembly steps needed to attach emitters to the end of a microfluidic channel. More recent efforts to make nanoelectrospray emitters from nanofluidic capillary slot and micromachined ultrasonic ejector arrays have faced similar challenges (Arscott, S.; Troadec, D. *Appl. Phys. Lett.* **2005**, *87*, 134101). None of these emitters has achieved desired flow rates of pL/min or less. In addition, no monolithic multinozzle emitter for nanoelectrospray mass spectrometry has ever been fabricated.

[0010] To increase the sensitivity of ESI further and to interface the emitters with lab-on-a-chip, breakthroughs in the design and fabrication of ultra-narrow emitters are clearly needed.

DISCLOSURE OF INVENTION AND BEST MODE FOR CARRYING OUT THE INVENTION

[0011] The embodiments of the invention are illustrated in the context of nanoelectrospray emitters for mass spectrometry. The skilled artisan will readily appreciate, however, that the materials and methods disclosed herein will have application in a number of other contexts where very small droplet size and very slow fluid flow rates are desirable.

[0012] The terms “nozzle,” “capillary,” and “tubule” are used interchangeably in this disclosure to mean a very thin tube out of which an analyte solution can flow and form small droplets. The term “emitter” is used to mean the assembly that includes both the nozzle(s) and a base chamber or tube that supplies an analyte solution to the nozzle(s). In the case of a single nozzle, the terms “emitter” and “nozzle” can refer to the same structure as there is a one-to-one correspondence between the nozzle and its base chamber; the base chamber can be thought of as a simple extension of the nozzle. The term “trench” is used to mean a groove or ditch in a surface. The term “channel” is used to mean a trench that has been enclosed to form a hollow elongated structure, such as a cylinder. A channel can have a circular, square, rectangular, triangular, or any polygonal or closed curve cross section. The term “monolithic” is used to mean consisting of one piece, solid and unbroken. In a monolithic structure there are no joints or seams.

The terms nanospray and nanoelectrospray are used interchangeably to mean electrospray at nanoliter/min flow rates. The term "femtoelectrospray" is used to describe electrospray at femtoliter/min flow rate.

[0013] Electrospray ionization (ESI) is a technique used in mass spectrometry to produce ions using a nozzle, capillary, or tubule. ESI is especially useful in producing ions from macromolecules because it overcomes the propensity of these molecules to fragment when ionized. One important variation on the basic electrospray technique, which generally offers better sensitivity, is nanospray ionization, in which the flow rate of the analyte solution is microliters/minute (μL/min) or nanoliters/minute (nL/min).

[0014] Silica (SiO_2) nanotubes can be especially useful as ESI emitters because of their ease of formation and possibilities for surface functionalization. In addition, their hydrophilic properties make silica electrospray emitters intrinsically more compatible with a wide variety of biomolecules than electrospray emitters made from hydrophobic polymers. Studies in nanofluidics have shown that biomolecules can indeed be transported through hydrophilic silica nanotubes.

[0015] In one embodiment of the invention, an electrospray emitter has one silica nozzle extending out from a larger silica base tube. The walls of the nozzle and the base tube form a monolithic whole. They are connected seamlessly and provide a sealed, continuous fluid path for analytes from the base tube to the nozzle. In one arrangement, the emitters protrude at least 10 μm from the base tube, *i.e.*, the open ends of the nozzles are at least 10 μm away from the base tube. In another arrangement, the emitters protrude about 150-200 μm from the base tube. In another arrangement, the emitters protrude about 100-150 μm from the base tube. In another arrangement, the emitters protrude about 50-100 μm from the base tube. In yet another arrangement, the emitters protrude about 10-50 μm from the base tube.

[0016] In another embodiment of the invention, there are several silica nozzles extending out from a larger silica base tube. The nozzles and base tube form a monolithic whole. In one arrangement, the nozzles each have an interior or channel cross sectional area of no more than 120 μm. In another arrangement, the nozzles each have an interior cross sectional area of no more than 100 μm. In one arrangement, the silica nozzles have a linear density of at least 100 per millimeter. In another arrangement, the nozzles have a linear density of at least 10 per millimeter. In another arrangement, the nozzles have an areal density of between about 104 and 106 nozzles per square millimeter.

[0017] In one embodiment, an electrospray emitter has a base tube and a plurality of smaller tubules connected seamlessly to the one end of the base tube. The structure is monolithic and defines sealed (*i.e.*, non-leaking), continuous fluid paths from the base tube through the tubules.

[0018] Embodiments of the invention include methods of making ESI emitters with very small inner nozzle cross sectional areas. The methods are variations on a general idea that involves making a silicon template, encasing the template in silica, and then removing the silicon, leaving a monolithic silica emitter structure. Two approaches to fabrication of ESI emitters can be thought of as follows: 1) a "bottom up" approach, wherein the template is made by the building up of very small starting structures; and 2) a "top down" approach, wherein the template is made by removing material from much larger starting structures.

Bottom Up Fabrication

[0019] In one embodiment of the invention, nanofabricated monolithic multinozzle (NM^2) emitters are formed using nanotechnology techniques. Silicon (Si) nanowire arrays are converted into silica nanotube arrays through a thermal oxidation-etching technique. The silica nanotubes retain the arrangement of the original silicon nanowire arrays. These oriented, robust silica nanotube arrays can be useful in nanoscale fluidic bioseparation, sensing, and catalysis, as well as for ESI in mass spectrometry.

[0020] Typically silica nanotubes have been synthesized within the pores of porous alumina membrane templates using a sol-gel coating technique. The alumina templates are then dissolved to liberate single silica nanotubes. But once the templates are removed, the silica nanotubes tend to bundle up and become less well oriented. Silica nanotubes, such as these prepared at low temperatures, have porous walls and are relatively fragile.

[0021] In an exemplary embodiment, the process to translate silicon nanowire arrays into silica nanotube arrays involves nine major steps as shown in Figures 2 and 3. In step 210, a silicon (110) wafer is diced into long slivers (5-10 cm) with rectangular cross-section (120 x 100μm). In other arrangements, silicon wafers with other orientations and other cross section sizes can be used. The slivers are cleaned in acetone and then in isopropanol with ultrasonication for 10 min each. In step 215, the slivers are coated with 10-20 μm SiO_2 using liquid phase chemical vapor deposition (LPCVD) at 450°C for 10-20 hours followed by annealing at 1000°C. A silicon sliver 300 with SiO_2 coating is shown in Figure 3a. In step 220, the SiO_2-coated slivers are dip-coated with a thin layer (300-800 nm) of PMMA (320 in Figure 3b) by immersion in a 5.5% PMMA/anisol solution and then cured at 150°C for 1 hour in a convection oven. In step 225, the silicon slivers are mechanically broken into short segments (*e.g.*, approximately 5 cm each). The broken line in Figure 3b indicates where such a break can occur. The broken end faces are fresh silicon (111) surfaces free of silicon dioxide and PMMA. In other embodiments, silicon surfaces having other orientations can be used. In step 230, 5 nm gold catalyst films are deposited onto a short segment by thermal evaporation or RF sputtering. Figure 3c shows the broken silicon segment 305 with SiO_2 310, PMMA 320 and gold 330 layers. In step 235, the segment is immersed in dichloromethane for 1 hour, which lifts off the PMMA and the gold films deposited thereon. After rinsing in isopropanol a few times, the segment has gold only on the broken end face. The surfaces of the opposite end and the four longer sides have the silicon dioxide layer 310 from step 215 exposed; the gold and the PMMA 320 have been removed. Figure 3d shows the silicon segment 305 with the SiO_2 layer 310 and the remaining gold film 335.

[0022] In step 240, silicon nanowires are grown on the gold-coated end face using $SiCl_4$-based chemical vapor deposition (CVD). Due to homogenous epitaxial growth, the silicon nanowires grow out approximately perpendicular to the end faces and are well-orientated and approximately parallel to the long axis of the segment. Figure 3e shows the silicon segment 305 with nanowires 340 protruding out from the surface. After nanowire growth, in step 245, the segment is transferred to a thermal oxidation furnace for dry oxygen oxidation at 950°C for 2 hours to transform the silicon nanowires into silicon/silica core-shell nanowires. In one arrangement, the silica shells have a diameter of about 100 nm. Figure 3f shows the nanowires with silica shells 350. In step 250, focused ion beam (FIB) milling is used to cut the nanowire ends (*e.g.*, along broken line in Figure 3f) to ensure that the distal ends or the nanowires are not sealed with either SiO_2 or gold and to adjust the nanowire lengths. Figure 3g shows the silicon segment 305 with the oxidized nanowire array 345. In some arrangements, not all nanowires are cut; the number and density of non-sealed nanowires can therefore be well controlled. The silica end of the silicon segment 305 is also removed, *e.g.*, by cutting. After cutting the nanowire ends, the silicon nanowire cores within the silica shells are exposed. In step 255, the segment is loaded into a XeF_2 etching chamber to remove silicon completely from both the nanowire cores and the interior of the silicon base segment. Thus the silicon cores are etched away to form a monolithic structure that contains a silica nanotube array continuously connected to a larger hollow silica base segment – a nanofabricated monolithic multinozzle (NM^2) emitter. Figure 3h shows the NM^2 structure 360 that includes a silica base chamber 365 with multiple silica nozzles 370. In optional step 260, at least a portion of the NM^2 emitter can be coated with platinum or gold using RF sputtering to ensure good electrical connections for nanoelectrospray.

[0023] In step 210, the size of the silicon slivers used in the process can also be chosen to yield (in step 255) segment bases with desirable inner diameters. The height and density of the nanowires can be controlled by varying the CVD time and conditions in step 240. The thickness of the silica shell and the inner diameter of the silica nanotube can be controlled by adjusting the thermal treatment temperature in step 245. In some embodiments, nanowires oxidized at 900ºC have a wall thickness around 55-65 nm, and nanowires oxidized at 800ºC have a wall thickness around 30-35 nm. In one embodiment, step 215, wherein the silicon sliver is coated with SiO_2 is eliminated. Later the outer surface of the silicon segment can be oxidized along with the silicon nanowires in step 245.

[0024] As discussed above in step 240, silicon nanowires are grown on the end face of the silicon segment. Figure 4 is a side view scanning electron microscope (SEM) image that shows an end portion 400 of a silicon segment and an array of silicon nanowires 410 extending out from the end portion 400.

[0025] As discussed above in step 250, FIB milling can be used to cut nanowire ends and expose silicon cores. Figure 5a is a schematic drawing that illustrates the method. A silicon segment 500 has silicon nanowires 510 extending from an end face. A silica shell 520 covers both the silicon segment 500 and the nanowires 510. Distal ends of the nanowires 510 are sealed with both silica 520 and gold particles 530. A line 540 indicates where a FIB cut is made. Figure 5b is a high magnification SEM image of silicon nanowires after cutting with FIB milling. The milling step removes gold and any silica from the nanowire ends, exposing the silicon cores so that the silicon can be etched away to form a silica nanotube array connected directly to the larger hollow silica tube.

[0026] The ability to adjust as desired the inner diameter and array density of silica nanotubes can lead to unprecedented low flow rates and therefore extremely high ionization efficiency. In addition, the nanotubes can be made to many desired lengths, (*e.g.*, on the order of 10 μm). A silicon nanotube has such a very high aspect ratio that it can confine an entire biomolecule, which can result in new translocation characteristics. The resulting nanofludics can accommodate even the minute sample size of a single cell with long enough spray times to provide high signal to noise ratios for mass spectrometry signals. Improved ionization efficiency and smaller droplet size can also increase the dynamic range. It may be possible to profile single tumor cells from a biopsy quantitatively followed by laser micro-dissection, or to probe single cells at different cell cycle and/or differentiation stages, thus elucidating the mechanisms underlying stem cell proliferation and differentiation.

[0027] The bottom up method can be summarized as growing silicon nanowires onto a clean silicon surface of a silicon base segment. The other surfaces of the base segment are coated with silica. Then the silicon nanowires are oxidized. The silica is removed from the distal ends of the base segment and the silicon nanowires to expose silicon. (The distal ends are the ends farthest away from the center of the structure.) Then silicon is removed from the interior of the structure to form a nanoelectrospray emitter.

Top Down Fabrication

[0028] In another embodiment of the invention, microfabricated monolithic multinozzle (M^3) emitters are made using micro-electro-mechanical system (MEMS) techniques. Microfluidic channels are etched and enclosed between silicon wafers by a combination of deep reactive ion etching and silicon fusion bonding techniques. These techniques are known to be useful in fabricating a wide variety of micromechanical devices.

[0029] In an exemplary embodiment, a novel silicon/silica-based microfabrication process for monolithic fabrication of biocompatible microfabricated monolithic multinozzle (M^3) emitters is shown in the schematic cross-section drawings in Figure 6 and in the flow diagram in Figure 7. Figure 6 illustrates the fabrication of only one channel. As the channel is defined by photolithography, it will be clear to a person of ordinary skill in the art that any number of channels, limited only by the photolithographic technique itself, can be fabricated on a single silicon wafer. Figure 6a shows a silicon wafer 600 with photoresist 610 patterned for photolithography according to step 710. The patterning step determines the length and width of the microfluidic channel. As is well known in the art of photolithography, there is a wide variety of lengths and widths that are possible. In some arrangements, the channel is not straight, but has a curved shape. Figure 6b shows the wafer 600 after time-multiplexed SF_6 etching and C_4F_8 passivation cycles have etched a channel or trench 620 according to step 720. Figure 6c shows a second silicon wafer 630 fusion bonded to the etched silicon wafer 600 to enclose the trench to form a microfluidic channel 625 as described in step 730. In the bonding step 730, the wafers are cleaned first with piranha solution and then are held together via hydrogen bonding between the silanol groups of the wafer surfaces. Subsequent high temperature annealing of the wafers causes the formation of the Si-O-Si covalent bonds at the wafer interface. The bond strength of these wafers has been found to be on the order of the yield strength of single-crystal silicon (~ 1 GPa). Figure 6d shows the structure with the ends removed, opening the channel 625, according to step 740. The ends of the structure can be removed using a wafer saw. Figure 6e shows the structure after it has been oxidized, according to step 750, leaving a layer 640 of SiO_2 along the exposed surfaces of the structure. Figure 6f shows the oxidized structure after one end of the structure has been removed, exposing a fresh silicon surface 650, according to step 760. Finally, in step 770, XeF_2 etching removes silicon from the exposed surface 650, leaving a nanoelectrospray nozzle 660 made of SiO_2 protruding from the remaining base structure 670, as shown in Figure 6g.

[0030] The process outlined in Figures 6 and 7 is straightforward, yet it is flexible enough to be used to fabricate very complicated structures. Structures that have been made using the method described in Figure 7 are shown in Figure 8. Figure 8a is a schematic perspective drawing of a two-nozzle emitter. Region 840 is a SiO_2 shell enclosing a base channel 820 and forming two nozzles 860. The box 800 is an unoxidized silicon base. Figures 8b and 8e are low magnification SEM images that show one nozzle and a five nozzle linear array, respectively. Figure 8c is a high magnification image of the single nozzle in Figure 8b. Figure 8f is a high magnification image of the five nozzles in Figure 8e. Figures 8d and 8g are high magnification images of a two nozzle array and a ten nozzle linear array, respectively.

[0031] Dimensions of the nozzle cross sections, their inter-nozzle spacing, the linear density of the nozzles and the base channel cross section dimensions are shown in Table I for the arrays in Figure 8.

Table I

Number of nozzles	Nozzle width x depth (μm)	Inter-nozzle spacing (μm)	Base channel width x depth (μm)	Linear density
1	10 x 12	n/a	100 x 12	n/a
2	10 x 12	40	100 x 12	20/mm
5	10 x 12	10	100 x 12	50/mm
10	2 x 8	8	100 x 8	100/mm

[0032] A linear density of 100 nozzles/mm, as has been achieved for the ten nozzle linear array, is unprecedented. Numerous nozzles result in lower back pressure and higher sensitivity, the latter of which is due to a much lower flow rate at each single nozzle for a given total flow rate at the base channel.

[0033] The top down method can be summarized as etching a trench into the surface of a silicon substrate, sealing a silicon wafer onto the surface of the substrate, thus enclosing the trench to form a channel, cutting the two channel ends, oxidizing structure cutting one end of the structure to expose the silicon core structure, and removing a portion of the silicon core to form a linear electrospray nozzle array .

[0034] The microfabricated emitters were tested to see how they perform in nanoelectrospray mass spectrometry. A microfabricated emitter containing a single nozzle (10 μm × 8 μm) was compared to a commercially available nanoelectrospray nozzle with an inner diameter of approximately 10 μm (Pt-coated, pulled fused-silica capillary SilicaTips^{TM}, New Objective, Inc). Both emitters were tested in a Q-TOF mass spectrometer (Waters, Inc.). The microfabricated emitters were made of conductive silicon; they were used without any additional metal coating.

[0035] The overall efficiency in electrospray mass spectrometry is defined as the number of analyte ions recorded at the detector divided by the number of analyte molecules sprayed. It therefore depends on three processes: desolvation, ionization, and transfer into the vacuum system. To make the comparison as meaningful as possible, most of the experimental parameters, such as sample used, parameters for the mass spectrometer, and the input flow rate have been kept identical. However the voltage applied to the devices and the position of the xyz stage that holds the emitter have been optimized for signal intensity. In these experiments, higher voltage (4.5 kV ~ 4.8 kV) was used for the microfabricated emitters than for the commercial tips (2.1 kV ~ 2.4 kV). It may be that depositing metal on the microfabricated emitters or using more conductive silicon may yield similar results with lower voltage. The mass spectrometry platform had been optimized for the commercial tips; more careful optimization of electrical and mechanical connections for the microfabricated emitters may also result in similar performance at a lower voltage.

[0036] A standard peptide, [Glu]-Fibrinopeptide B (GFP B, M.W. = 1570.57) was used in one test. The GFP B solution (1 μM) was delivered to the emitters at a flow rate of 600 nL/min. Figures 9a and 9b show the mass spectra obtained from the microfabricated emitter and the commercial emitter, respectively. The isotopic distributions of doubly-charged ions of GFP B can be seen clearly in both cases with a similar magnitude base peak intensity (BPI) of about 1,000 per scan. Thus the resolution and the sensitivity of the microfabricated emitter (Figure 9a) compare well to those of state-of-the-art commercial emitters (Figure 9b).

[0037] The microfabricated emitter was also tested in comparison to the commercial emitter for detecting bovine serum albumin (BSA, ~ 67 kDa), a high molecular weight protein. The mass spectra, accumulated for 10 minutes are shown in Figures 10a and 10b for the microfabricated emitter and the commercial emitter, respectively. Charge state distribution and base peak intensity were similar for both emitters. Thirty-eight or more charge states of the protein can be seen with the highest peak at around m/z = 1,340, which corresponds to about 50 positive charges.

[0038] Figures 11a and 11b show that the stability of the microfabricated emitters (relative standard deviation, RSD ~ 4.5 %) is comparable to that of the commercial emitter (RSD ~ 4.2 %).

[0039] Performance comparisons were made between one-nozzle (10 μm × 12 μm), two-nozzle (10 μm × 12 μm), and five-nozzle emitters (8 μm × 2 μm), all made by using the same microfabrication process and without additional metal coatings. Myoglobin (~17 kD) analyte was flowed through the base channel at a constant rate of 600 nL/min. On average, the flow rate at the nozzle was about 600 nL/min for the one-nozzle, 120 nL/min for the two-nozzle, and 60 nL/min for the five-nozzle emitter. The nozzles were watched and it was confirmed that electrospray spewed from each of the nozzles. The mass spectra obtained from the emitters are shown in Figures 12a, 12b, 12c. The multinozzle emitters (Figures 12b, 12c) show slightly higher sensitivity than the one-nozzle emitter (Figure 12a). Multinozzle emitters are expected to ease back pressure and clogging problems that plague single-nozzle emitters, especially as the channel downsizes to submicron scale.

[0040] In another embodiment of the invention, a two dimensional array of M^3 emitters contains two rows of linear arrays. The steps for this process are analogous to those for the linear array (Figure 7) and are outlined in Figure 13. In step 1310, two silicon substrates are patterned with photoresist to determine the lengths and widths of the microfluidic channels. In step 1320, the substrates are etched to carve out trenches that will become the microfluidic channels. Time-multiplexed SF_6 etching and C_4F_8 passivation cycles can be used to etch the trenches. In step 1330, the etched substrates are each bonded to an opposite surface of an ultrathin silicon bonding wafer, forming a “sandwich” structure. The single bonding wafer closes the trenches on both etched substrates, forming the microfluidic channels. The ultrathin silicon bonding wafer can be as thin as 200 μm. In some arrangements the bonding wafer is less than 100 μm in thickness. In yet other arrangements, the bonding wafer is between about 30 μm and 50 μm in thickness. The substrates and the bonding wafer can be cleaned first with piranha solution. Then the substrates and the bonding wafer are held together via hydrogen bonding between the silanol groups of the surfaces. Subsequent high temperature annealing of the wafers causes the formation of the Si-O-Si covalent bonds at the interfaces. In step 1340, the ends of the sandwich structure are removed, opening all channels. In step 1350, the structure is oxidized, leaving a layer of SiO_2 along the exposed surfaces. In step 1360, one end of the structure is removed, exposing a fresh silicon surface. Finally, in step 1370, XeF_2 etching removes silicon from the exposed surface, leaving a two-layer, two-dimensional array of

M^3 silica emitters made protruding from the remaining base structure.

[0041] In another embodiment of the invention, two dimensional arrays of M^3 emitters are made by stacking several linear nozzle arrays, such as those shown in Figure 8. Such a two dimensional array has a geometry reminiscent of the two dimensional arrays produced by the bottom up method described above. The linear arrays in Figure 8 were made using standard silicon wafers with thicknesses of about 500μm. Thinner wafers can be used in order to reduce the distance between the linear arrays. In one arrangement, a thin silicon wafer can be used for the lithography steps (steps 710, 720 in Figure 7), and an even thinner wafer can be used to bond to the etched wafer (step 730 in Figure 7). For example, when silicon wafers with a thickness of about 100 μm are used to make linear arrays using the process discussed in reference to Figure 7, the resulting areal nozzle density is $10^3/mm^2$. With thinner bonding wafers even higher densities can be achieved. In comparison, a nozzle array previously fabricated via an out-of-plane approach has an areal density in the range of about 2.5 nozzles/mm^3 (Deng, W. W.; Klemic, J. F.; Li, X. H.; Reed, M. A.; Gomez, A. *J. Aerosol Sci.* **2006**, *37*, 696-714) – two orders of magnitude less than for the wafer arrays made by stacking M^3 emitters.

[0042] With further optimization and using e-beam lithography or nano-imprint technology, it is also possible to fabricate M^3 emitters down to submicron sizes and with densities up to 10^5 nozzles/mm^2 or more.

[0043] Using the same process and by changing only the layout, complex built-in structures such as a separation column, a sample reservoir, and a particle filter can be monolithically fabricated along with and in fluid communication with the M^3 emitters. In another embodiment, the inorganic nanotube nanofluidic nanotube arrays are integrated with a fully-controlled microfludics and nanofludics system. Single cells can be manipulated and digested in separate chambers before being analyzed by femtoelectrospray mass spectrometry.

[0044] The silica surfaces of the NM^2 or M^3 emitters can also be modified. In one embodiment, the silica can be deactivated using a silanization fluid to minimize nonspecific sample adsorption in the inner walls of the emitters.

[0045] This invention has been described herein in considerable detail to provide those skilled in the art with information relevant to apply the novel principles and to construct and use such specialized components as are required. However, it is to be understood that the invention can be carried out by different equipment, materials and devices, and that various modifications, both as to the equipment and operating procedures, can be accomplished without departing from the scope of the invention itself.

BRIEF DESCRIPTION OF THE DRAWINGS

[0046] Figure 1 is a simple diagram outlining the main components of a mass spectrometer.

[0047] Figure 2 is a flow chart that shows the steps for fabricating a NM^2 emitter, according to an embodiment of the invention.

[0048] Figures 3a-3h are a series of schematic cross section drawings that illustrate the steps for fabricating a nanoelectrospray emitter, according to an embodiment of the invention.

[0049] Figure 4 is a side view SEM image of a silicon nanowire array grown onto the end face of a silicon segment.

[0050] Figure 5a is schematic cross section drawing that illustrates FIB milling of oxidized silicon nanowires. Figure 5b is a SEM image of oxidized silicon nanowires after FIB milling.

[0051] Figures 6a-6g are a series of schematic cross section drawings that illustrate the steps for fabricating an M^3 emitter, according to an embodiment of the invention.

[0052] Figure 7 is a flow chart that shows the steps for fabricating an M^3 emitter, according to an embodiment of the invention.

[0053] Figure 8a is a schematic drawing that shows a nanoelectrospray emitter with two protruding nozzles.

[0054] Figures 8b-8g are SEM images of various M^3 emitters.

[0055] Figures 9a and 9b show mass spectra of 1 μM GFP B obtained from a microfabricated single-nozzle emitter and a commercial emitter, respectively.

[0056] Figures 10a and 10b show mass spectra of 1 μM BSA obtained from a microfabricated single-nozzle emitter and a commercial emitter, respectively.

[0057] Figures 11a and 11b show total ion counts over time for the 1 μM BSA spectra in Figures 10a and 10b obtained from a microfabricated single-nozzle emitter and a commercial emitter, respectively.

[0058] Figures 12a, 12b, and 12c show mass spectra of 1 μM myoglobin obtained from a one-nozzle emitter, a two-nozzle emitter, and a five-nozzle emitter, respectively, all microfabricated according to embodiments of the invention.

[0059] Figure 13 is a flow chart that shows the steps for fabricating a multi-layer, two dimensional M^3 emitter, according to an embodiment of the invention.

INDUSTRIAL APPLICABILITY

[0060] The processes described herein for fabricating monolithic multinozzle emitters for nanoelectrospray mass spectrometry are significantly simplified as compared to the current state of the art. The emitters are formed monolithicly, as one piece, thereby avoiding the reliability problems associated with joining very small components. A further distinct advantage of these processes is that they can be scaled up easily for large-scale manufacturing. The emitters can be mass-produced using current microfabrication and nanofabrication technology and can be interfaced readily with microfluidic channels in a lab-on-a-chip proteomics system. Furthermore, microfabricated monolithic multinozzle (M^3) emitters and nanofabricated monolithic multinozzle (NM^2) emitters have the potential to improve sensitivity for nanoelectrospray mass spectrometry.

[0061] The emitter devices described herein have distinct advantages over the current-state-of- the-art. First, a silicon/silica microfluidic channel or base tube has been integrated monolithically with a nanoelectrospray emitter. To date there have been no such monolithic structures available. Such a monolithic structure can pave the way to the large scale integration of nanoelectrospray emitter structures onto lab-on-a-chip devices so that a variety of experiments can be performed easily on the same sample in proteomics and for other applications. Second, this is the first reported electrospray device that has multiple nozzles. NM^2 and M^3 nanoelectrospray emitters have lower back pressure and yield higher mass spectrometry sensitivity. Furthermore the devices can be fabricated using known nanofabrication and microfabrication processes. As an additional benefit, the emitters described herein provide a means to study systematically the electrospray ionization process, as there is a wide range of sizes and densities of nozzles that can be fabricated for a variety of experiments. When NM^2 and M^3 emitters are integrated into the ion source of a mass spectrometer, they can provide higher sensitivity in mass spectrometry for proteomic and other applications than has been seen before. With further emitter optimization, additional performance enhancement is expected.

WE CLAIM:

1. An electrospray emitter comprising:

a first silica nozzle extending out from a larger silica base tube;

wherein the walls of the nozzle and the base tube form a monolithic whole.

2. The emitter of Claim 1, further comprising:

a second silica nozzle extending out from the larger silica base tube;

wherein the first nozzle, the second nozzle and the base tube form a monolithic whole.

3. The emitter of Claim 2 wherein each silica nozzle has an interior cross sectional area of no more than 120 μm.

4. The emitter of Claim 2 wherein each silica nozzle has an interior cross sectional area of no more than 16 μm.

5. The emitter of Claim 2 wherein the silica nozzles have a linear density of at least 100 per millimeter.

6. The emitter of Claim 5 wherein the silica nozzles have a linear density of at least 10 per millimeter.

7. The emitter of Claim 2 wherein the plurality of silica nozzles have an areal density between about 10^4 and 10^6 nozzles per square millimeter.

8. A structure comprising:

a base tube having a first end and a second end; and

a plurality of smaller tubules, each tubule having a first end and a second end, the first ends of the tubules seamlessly connected to the second end of the base tube and the tubules extending out from the base tube;

wherein the structure is monolithic and defines sealed, continuous fluid paths from the first end of the base tube to the second ends of the tubules.

9. The structure of Claim 8, wherein the second ends of the tubules are between 50 μm and 200 μm from the second end of the base tube.

10. A method of forming an electrospray emitter comprising:

providing a three dimensional template made of silicon;

surrounding the template with silica to form a compound structure;

removing the silica from ends of the compound structure to expose a portion of the silicon; and

removing the silicon from the compound structure.

11. The method of Claim 10 wherein providing a three dimensional template comprises:

providing a silicon base; and

growing silicon nanowires from one face of the silicon base.

12. The method of Claim 10 wherein providing a three dimensional template comprises:

providing a silicon substrate;

forming a first trench into a surface of the substrate;

sealing a silicon wafer onto the surface of the substrate, enclosing the trench to form a channel; and

opening two ends of the channel.

13. The method of Claim 10 wherein surrounding the template with silica comprises either depositing SiO_2 onto the template, oxidizing the template, or a combination thereof.

14. A method of forming a nanoelectrospray emitter comprising:

providing a silicon base with a silica coating, the silicon base having a first end with no silica coating;

growing silicon nanowires from the first end of the base;

oxidizing the silicon nanowires to form a silica/silicon shell/core structure;

removing silica from the distal end of the base and from the distal end of the nanowires to expose silicon; and

removing silicon from the shell/core structure to form a nanoelectrospray emitter.

15. A method of forming an electrospray emitter comprising:

providing a silicon substrate having a first surface;

etching a first trench into the first surface of the substrate;

sealing a silicon wafer onto the first surface of the substrate, enclosing the trench to form a channel, and forming a silicon core structure;

cutting the core structure to expose two channel ends;

oxidizing the core structure to form a silica/silicon shell/core structure;

cutting one end of the shell/core structure to expose the silicon core structure; and

removing a portion of the silicon core structure to form a linear electrospray nozzle array.

16. The method of Claim 15, further comprising:

providing a plurality of linear electrospray nozzle arrays;

forming a stack of the linear arrays one on top of another so that the cut ends of the shell/core structures make up one side of the stack; and

bonding the linear arrays together in the stack.

17. A method of forming an electrospray emitter comprising:

providing a first silicon substrate having a first surface;

etching a first trench into the first surface of the first substrate;

providing a second silicon substrate having a first surface;

etching a second trench into the first surface of the second substrate;

providing an ultra thin silicon wafer having a first surface and a second surface;

sealing the first surface of the silicon wafer to the first surface of the first substrate, enclosing the first trench to form a first channel;

sealing the second surface of the silicon wafer to the first surface of the second substrate, enclosing the second trench to form a second channel;

cutting two ends of the first channel and two ends of the second channel to expose the channels;

oxidizing to form a silica/silicon shell/core structure;

cutting one end of the shell/core structure to expose silicon; and

removing a portion of the silicon to form an electrospray nozzle array.

18. A method of improving sensitivity in mass spectrometry comprising integrating the electrospray nozzle of Claim 2 into the ion source of a mass spectrometer.

19. A method of performing a variety of experiments on a protein sample, comprising integrating the electrospray nozzle of Claim 2 into a lab-on-a-chip.

20. A method of studying ionization mechanisms in mass spectrometry comprising successively integrating each of a plurality of emitters of Claim 2 into an ion source of a mass spectrometer, each of the emitters having different inner cross section areas and different nozzle densities.

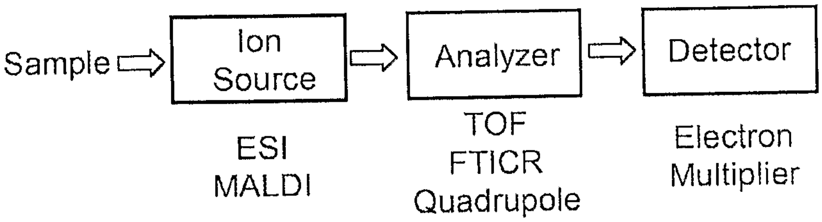

Sample
Ion Source
Analyzer
Detector
ESI
MALDI
TOF
FTICR
Quadrupole
Electron Multiplier

FIG. 1

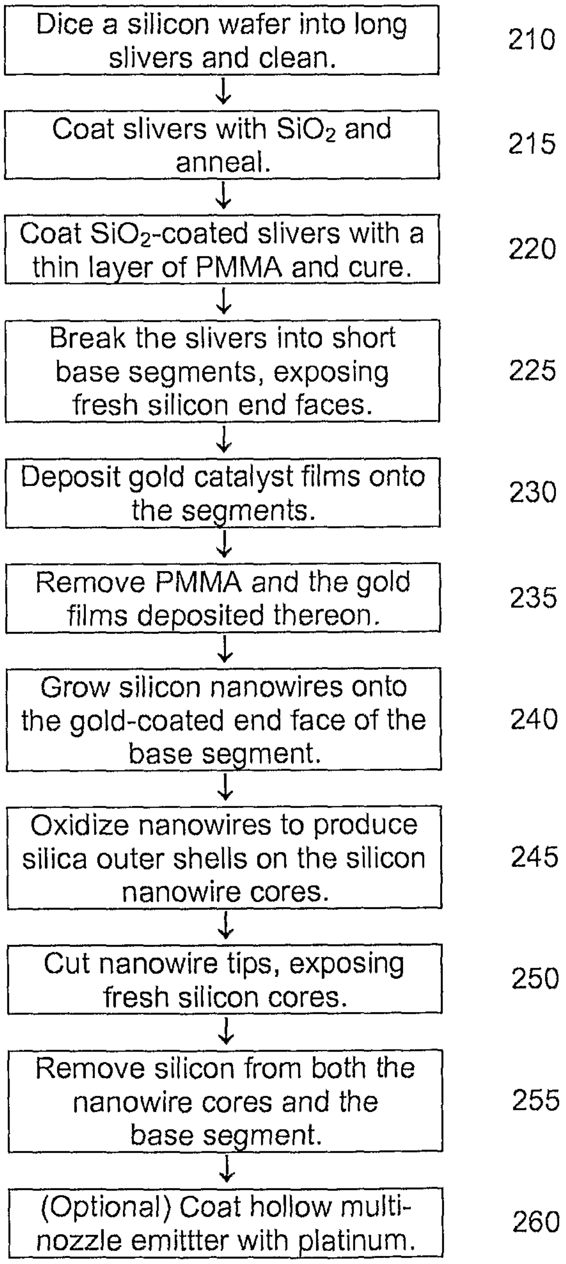

Dice a silicon wafer into long slivers and clean.
210
Coat slivers with SiO2 and anneal.
215
Coat SiO2-coated slivers with a thin layer of PMMA and cure.
220
Break the slivers into short base segments, exposing fresh silicon end faces.
225
Deposit gold catalyst films onto the segments.
230
Remove PMMA and the gold films deposited thereon.
235
Grow silicon nanowires onto the gold-coated end face of the base segment.
240
Oxidize nanowires to produce silica outer shells on the silicon nanowire cores.
245
Cut nanowire tips, exposing fresh silicon cores.
250
Remove silicon from both the nanowire cores and the base segment.
255
(Optional) Coat hollow multi-nozzle emittter with platinum.
260

FIG. 2

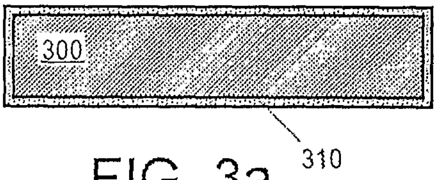


FIG. 3a

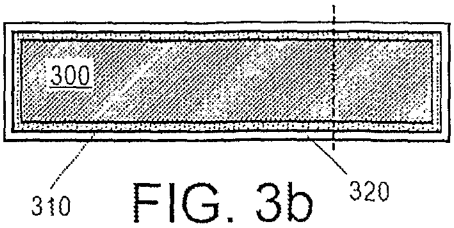


FIG. 3b

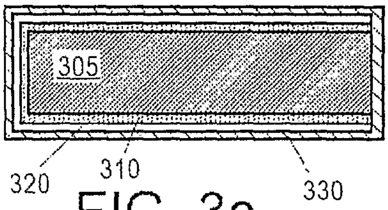


FIG. 3c

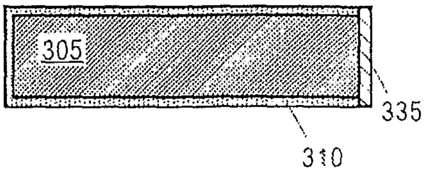


FIG. 3d

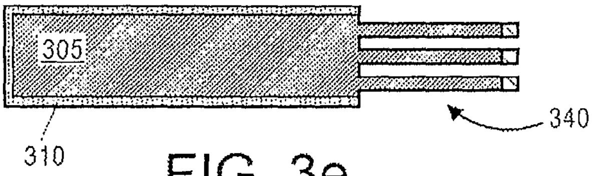


FIG. 3e

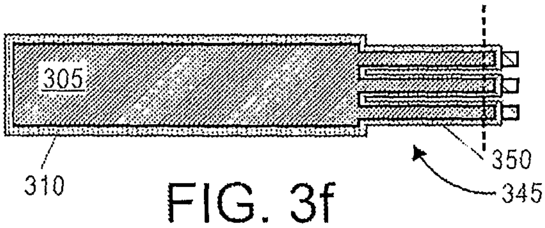


FIG. 3f

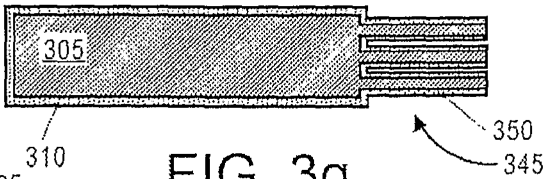


FIG. 3g

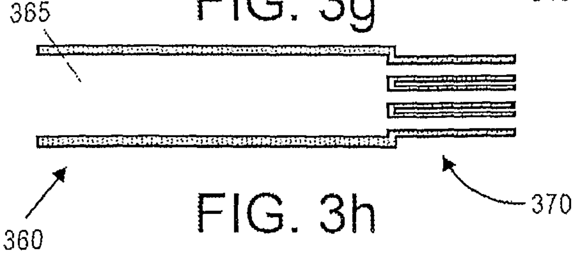


FIG. 3h

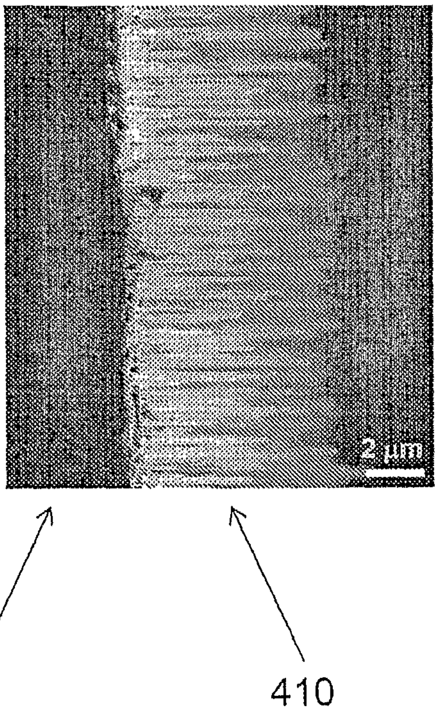


FIG. 4

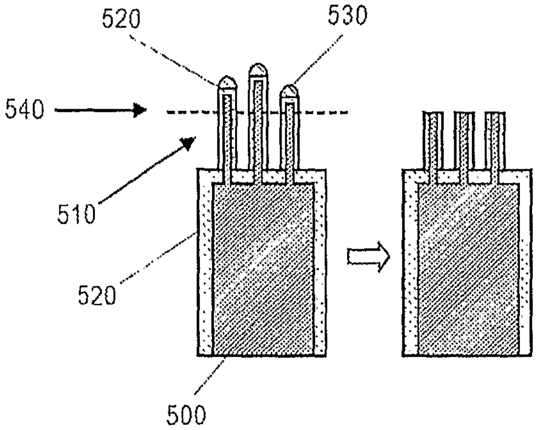


FIG. 5a

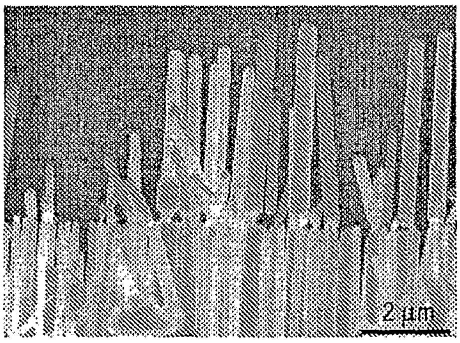


FIG. 5b

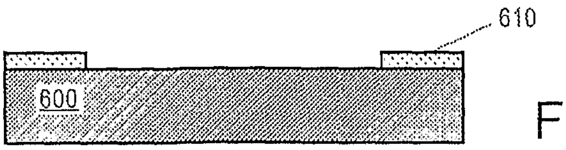


FIG. 6a

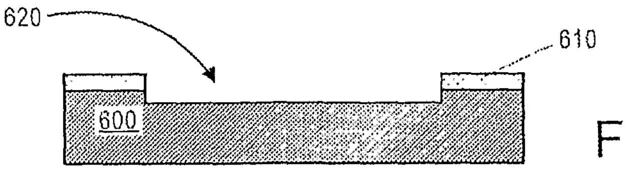


FIG. 6b

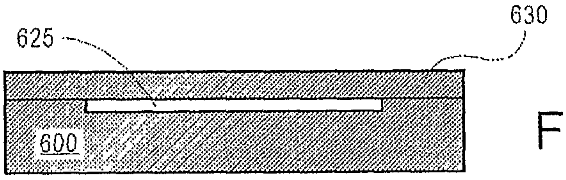


FIG. 6c

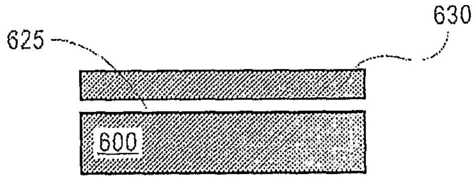


FIG. 6d

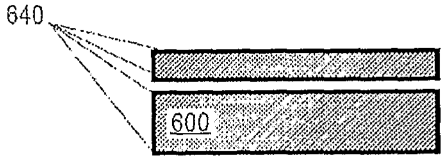


FIG. 6e

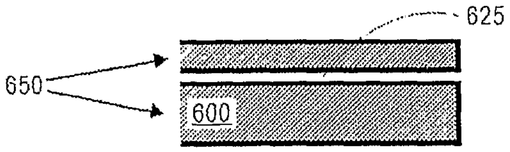


FIG. 6f

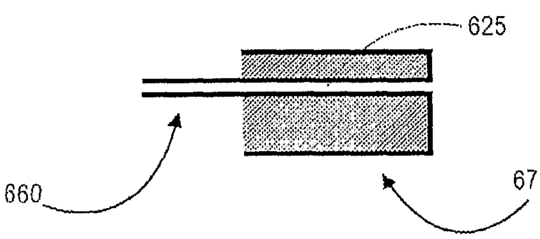


FIG. 6g

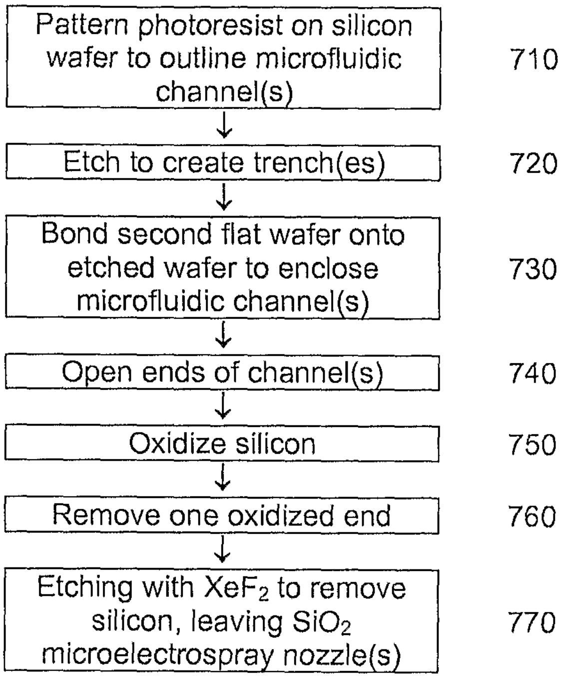
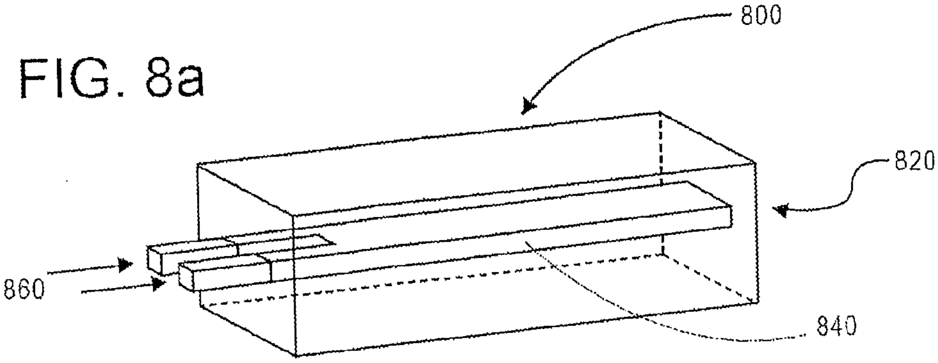

Pattern photoresist on silicon wafer to outline microfluidic channel(s)
710
Etch to create trench(es)
720
Bond second flat wafer onto etched wafer to enclose microfluidic channel(s)
730
Open ends of channel(s)
740
Oxidize silicon
750
Remove one oxidized end
760
Etching with XeF_2 to remove silicon, leaving SiO_2 microelectrospray nozzle(s)
770

FIG. 7

FIG. 8a



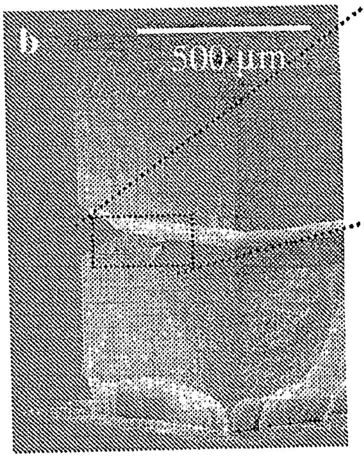


FIG. 8b

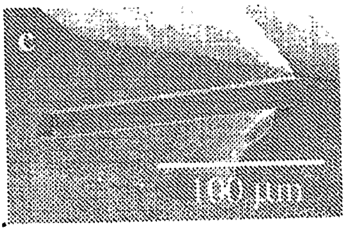


FIG. 8c

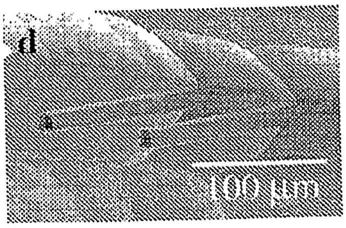


FIG. 8d

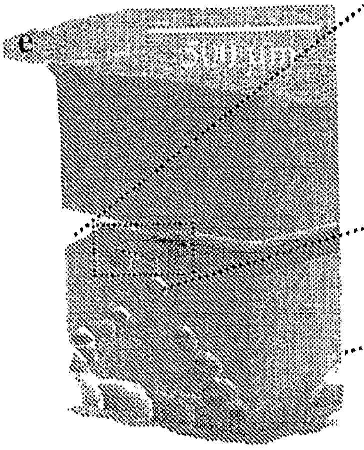


FIG. 8e

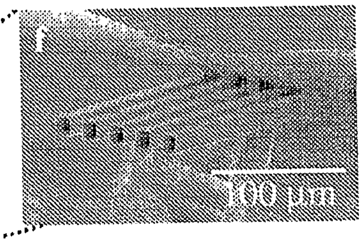


FIG. 8f

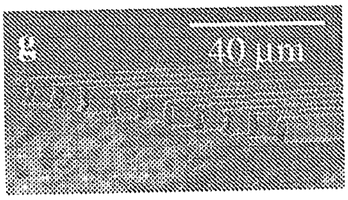


FIG. 8g

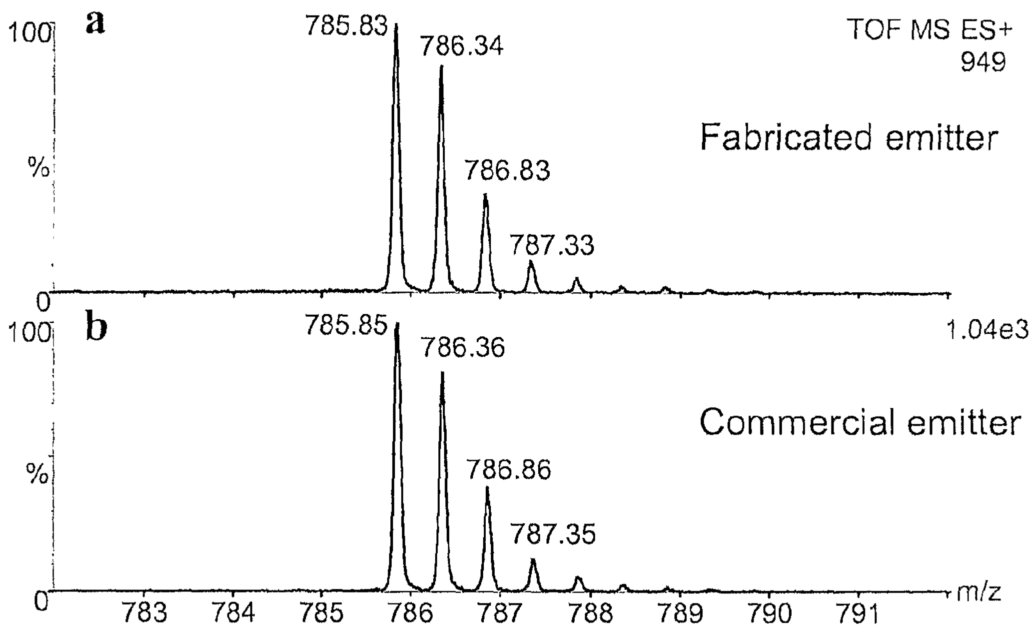

a
100
%
0
785.83
786.34
786.83
787.33
TOF MS ES+
949
Fabricated emitter
b
100
%
0
785.85
786.36
786.86
787.35
1.04e3
Commercial emitter
783
784
785
786
787
788
789
790
791
m/z

FIG. 9

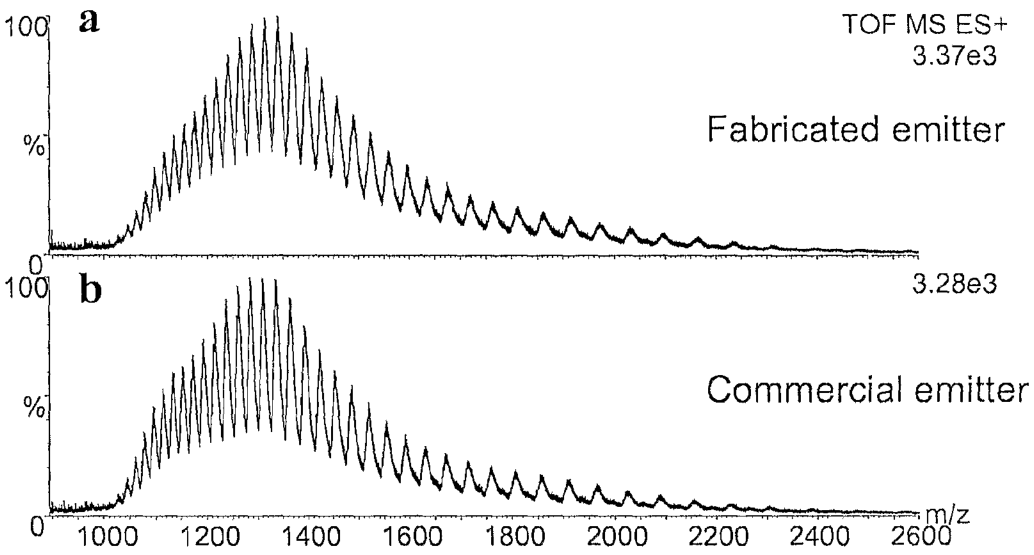

100
a
TOF MS ES+
3.37e3
Fabricated emitter
%
0
100
b
3.28e3
Commercial emitter
%
0
1000
1200
1400
1600
1800
2000
2200
2400
2600
m/z

FIG. 10

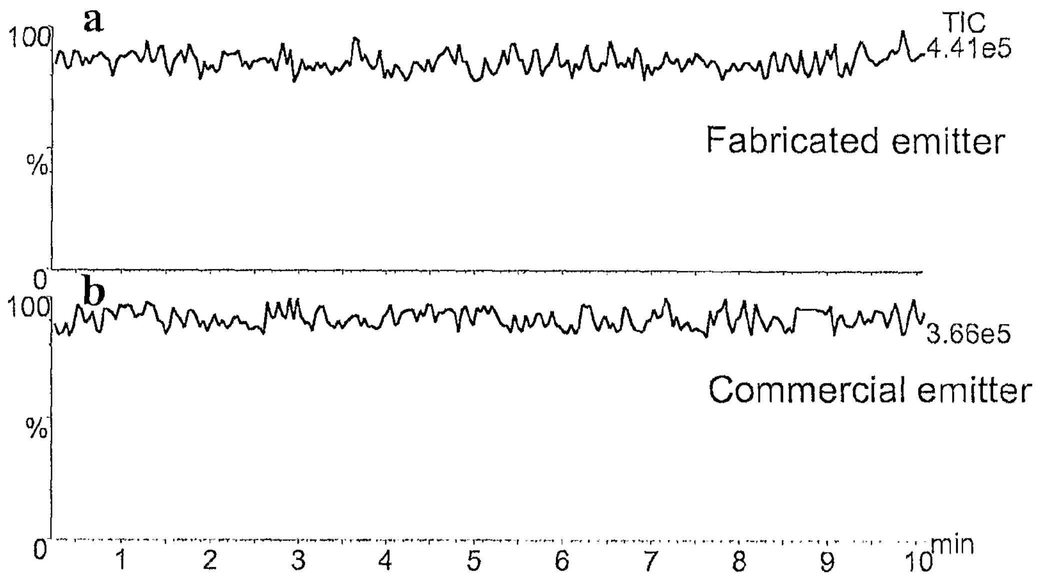

a
TIC
4.41e5
100
%
0
Fabricated emitter
b
100
3.66e5
%
0
Commercial emitter
1
2
3
4
5
6
7
8
9
10
min

FIG. 11

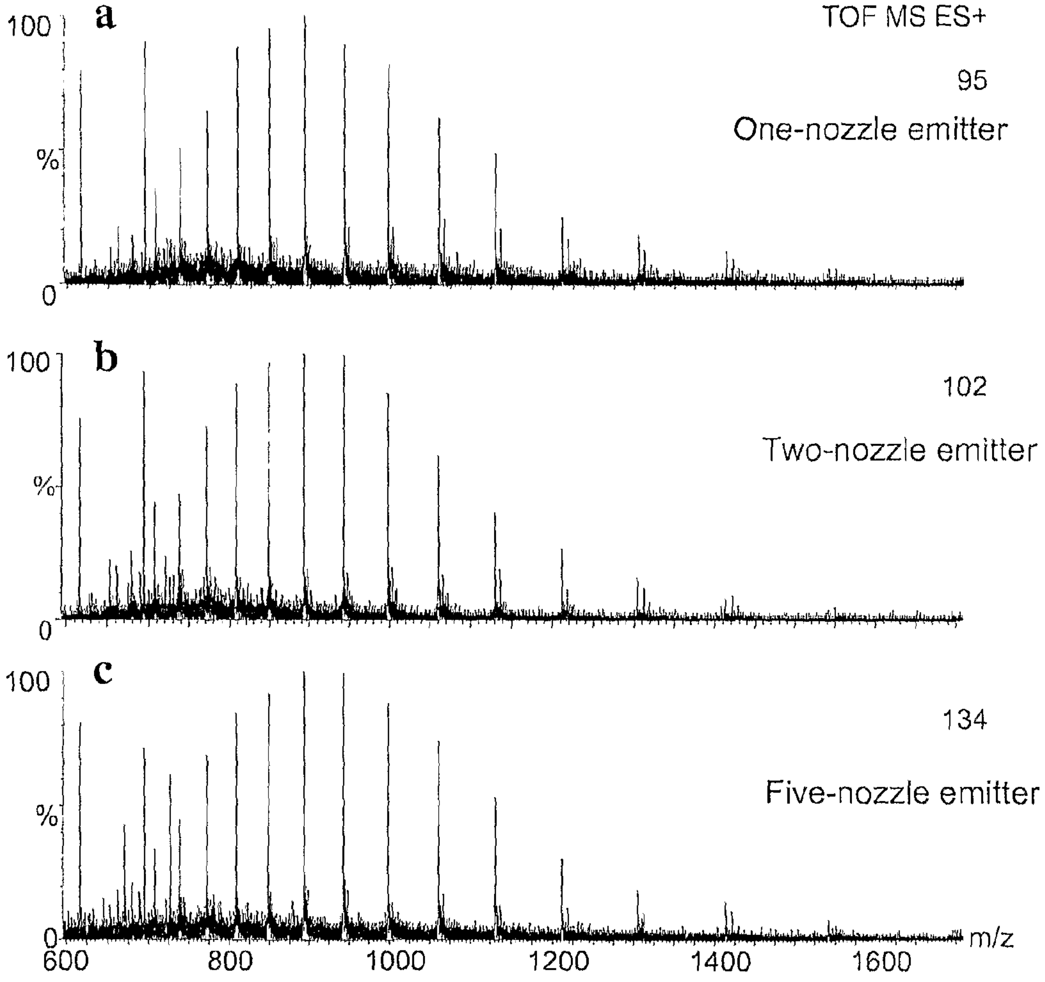

a
TOF MS ES+
95
One-nozzle emitter
100
%
0
b
102
Two-nozzle emitter
100
%
0
c
134
Five-nozzle emitter
100
%
0
600
800
1000
1200
1400
1600
m/z

FIG. 12

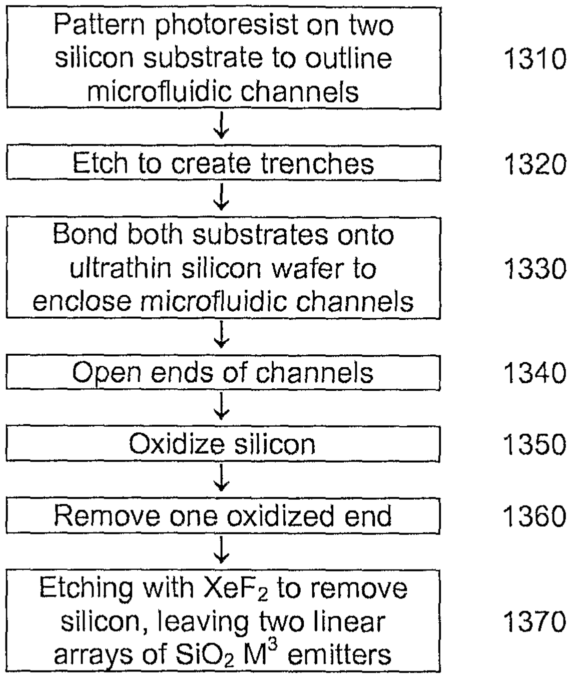

Pattern photoresist on two silicon substrate to outline microfluidic channels
1310
Etch to create trenches
1320
Bond both substrates onto ultrathin silicon wafer to enclose microfluidic channels
1330
Open ends of channels
1340
Oxidize silicon
1350
Remove one oxidized end
1360
Etching with XeF_2 to remove silicon, leaving two linear arrays of SiO_2 M^3 emitters
1370

FIG. 13