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(54) **FORMATION OF A MICROFLUIDIC ARRAY**

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(57) **ABSTRACT**

The invention relates to a method of forming a microfluidic array comprising at least one channel of semi-circular section, comprising the following steps:

bringing into contact a first liquid (7) with an array of electrodes (3) of a microfluidic chip (1) comprising at least one pair of substantially parallel and coplanar electrodes (3a, 3b) arranged on a substrate (4),

activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure (9) comprising at least one fluidic finger (9a), and

using said fluidic structure as a mould to form said microfluidic array by solidification or hardening of a second liquid (11) deposited on the microfluidic chip and hugging the shape of said fluidic structure.

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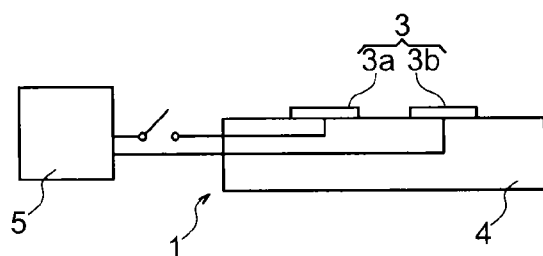


FIG. 1A

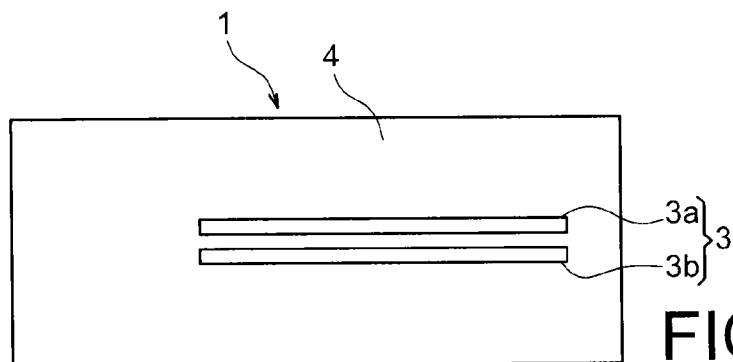


FIG. 1B

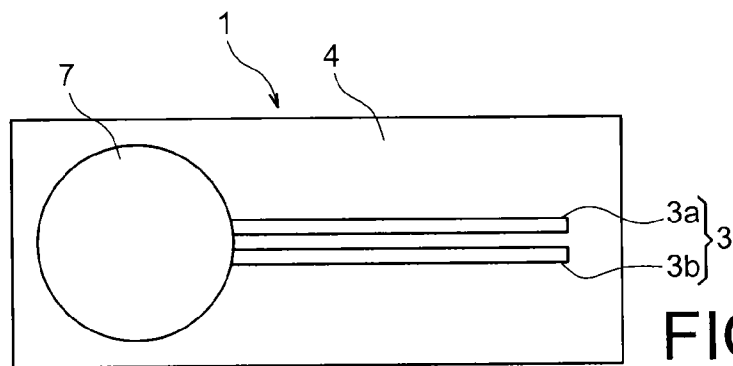


FIG. 1C

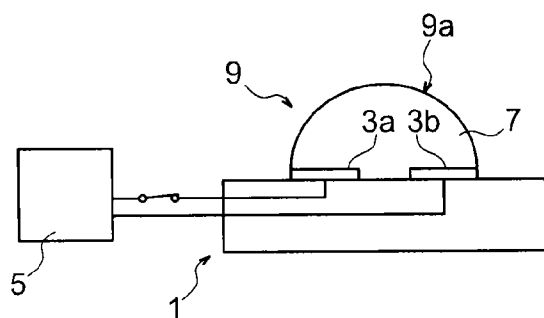
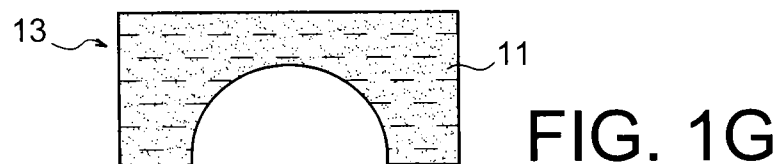
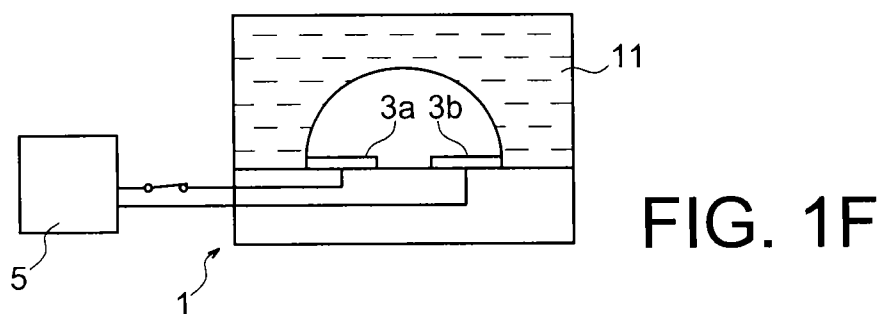
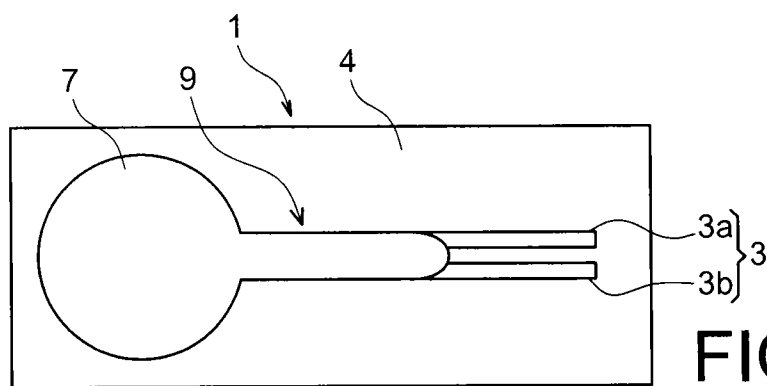


FIG. 1D



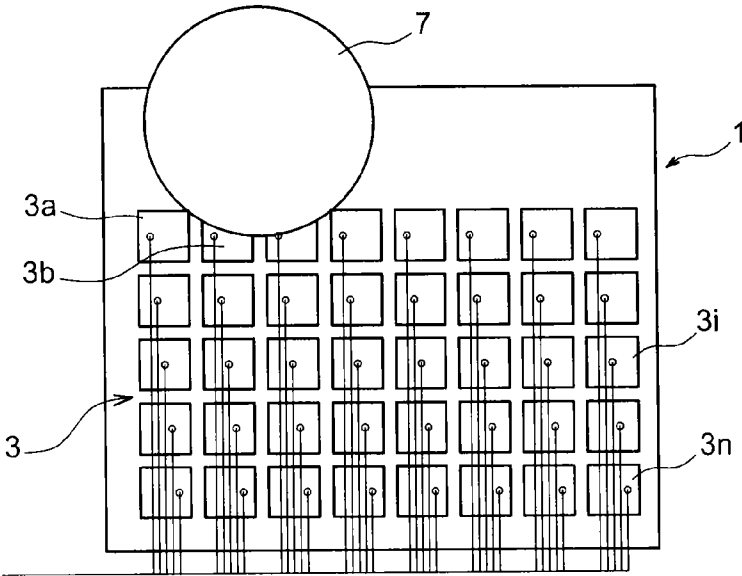


FIG. 2A

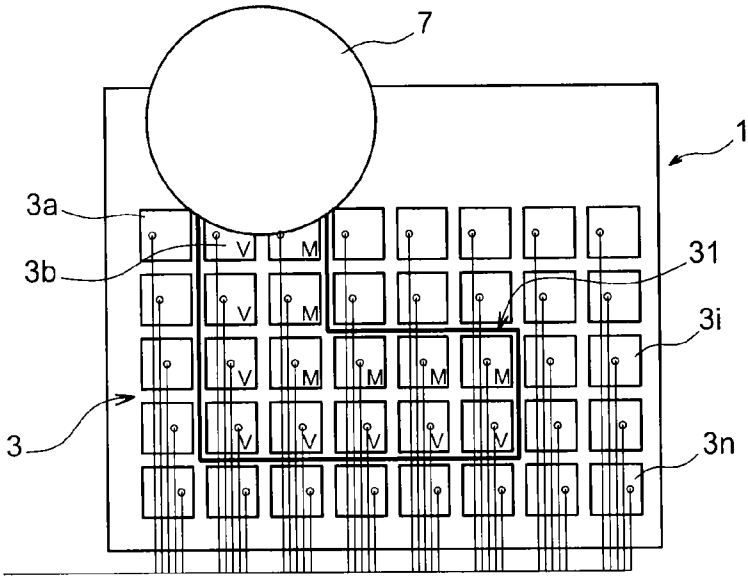


FIG. 2B

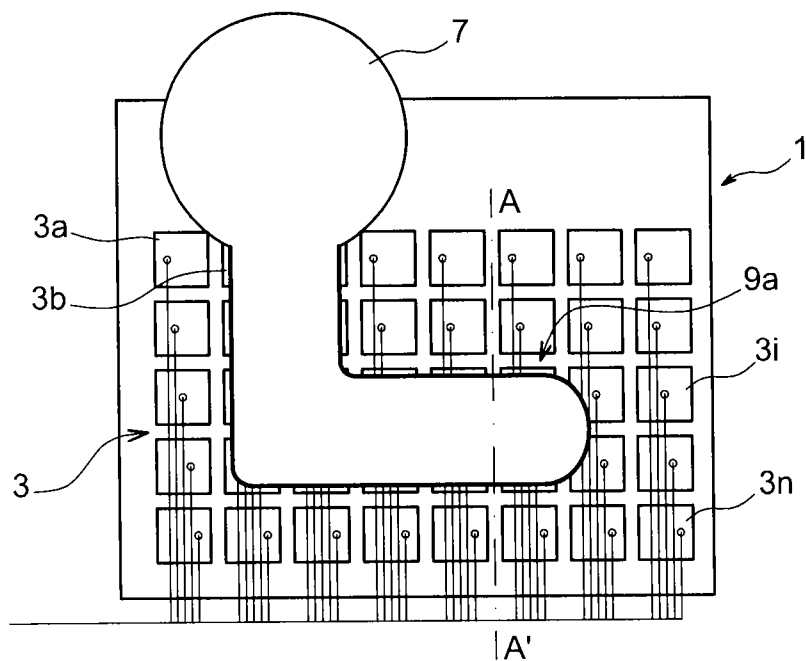


FIG. 2C

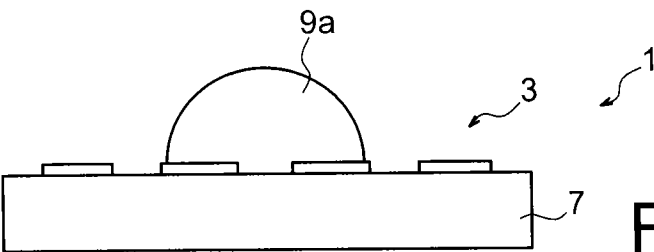


FIG. 2D

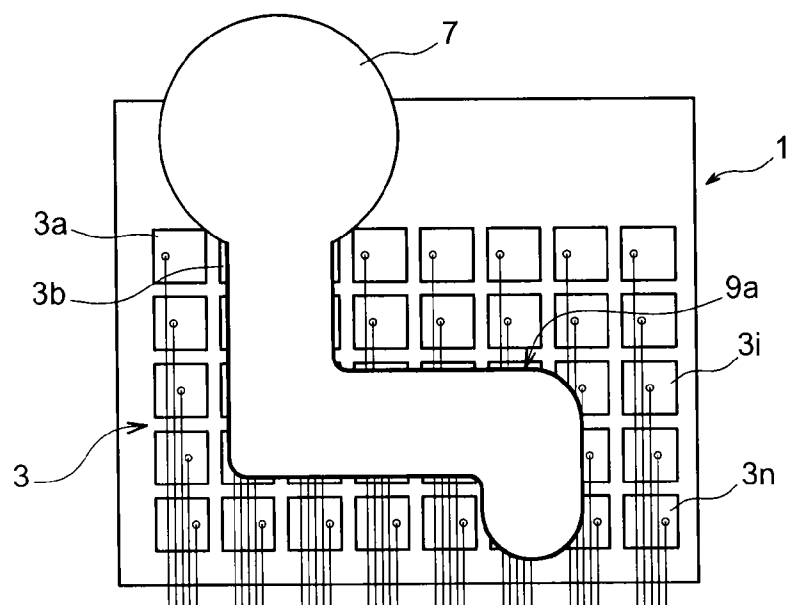


FIG. 2E

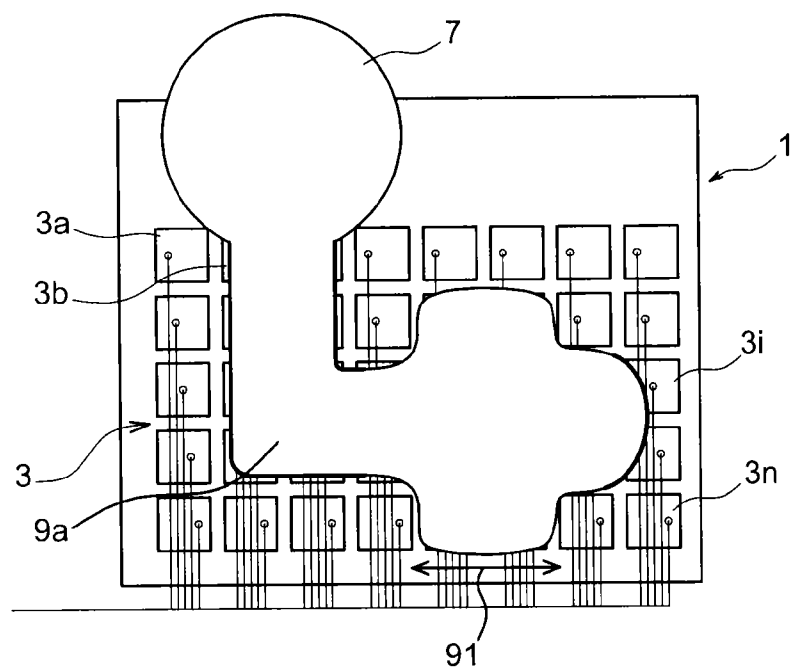


FIG. 2F

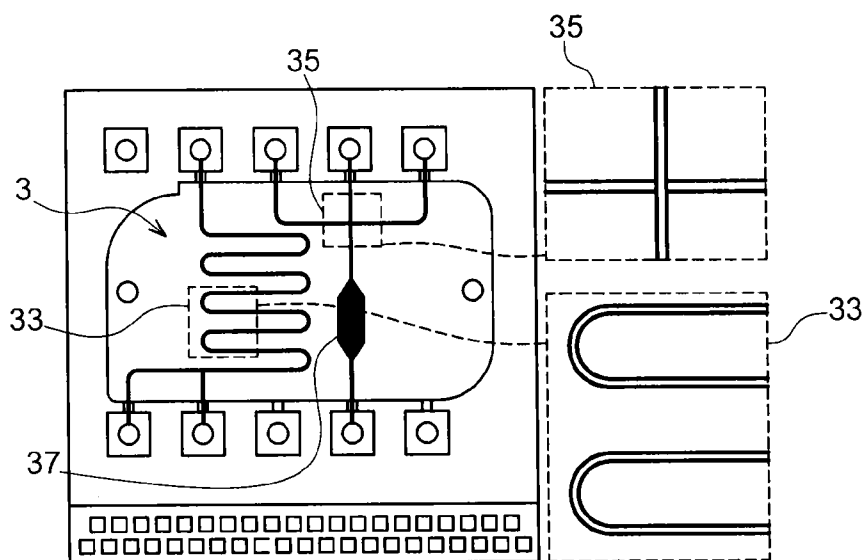


FIG. 3A

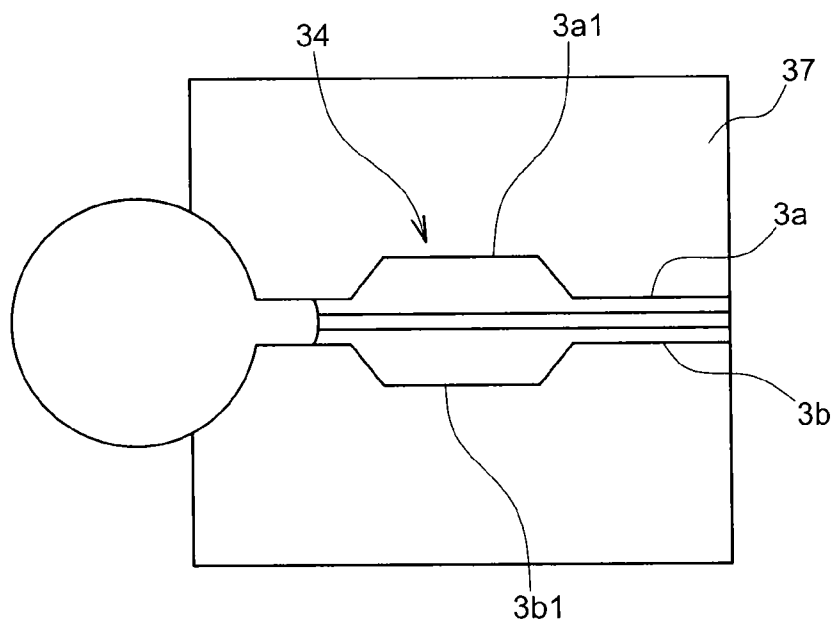


FIG. 3B

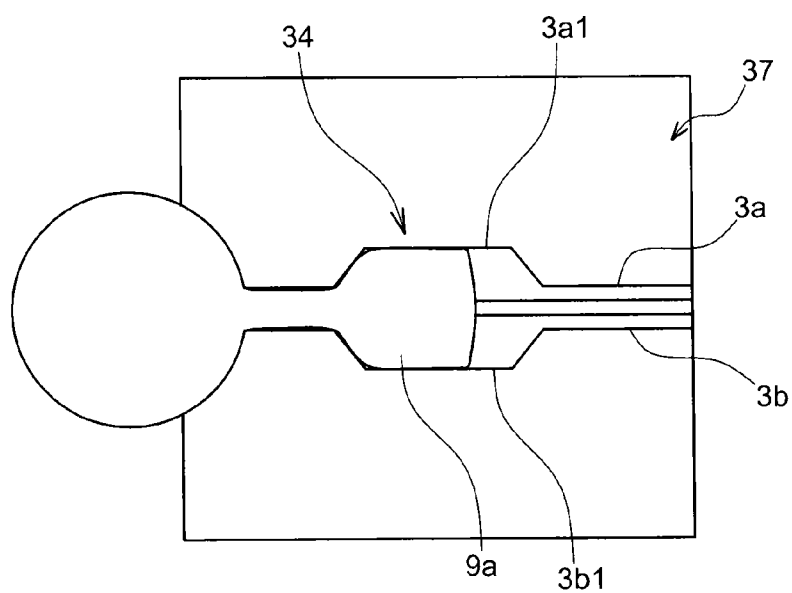


FIG. 3C

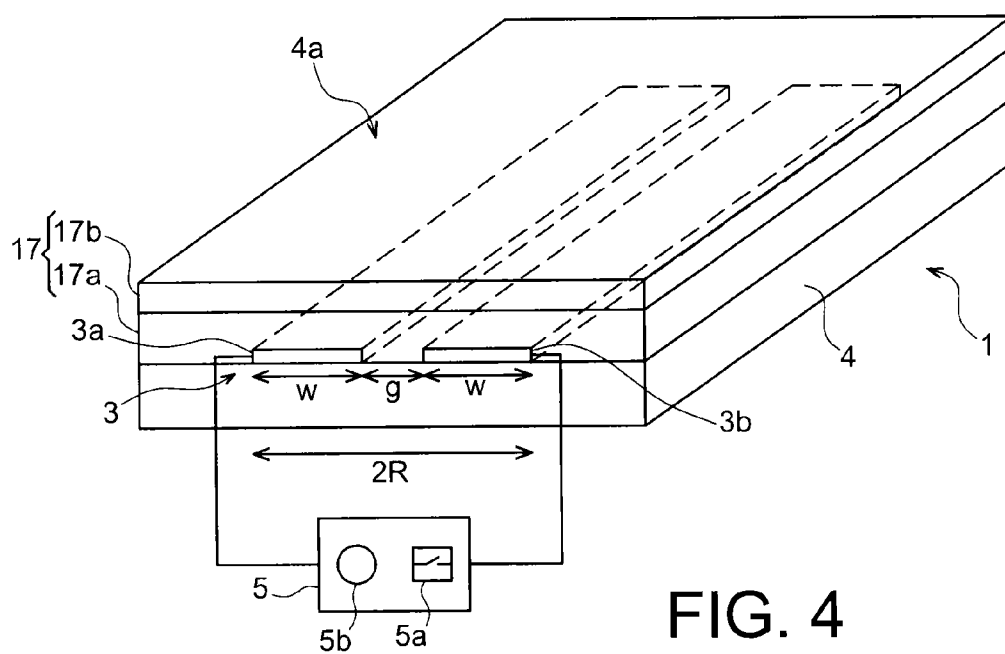
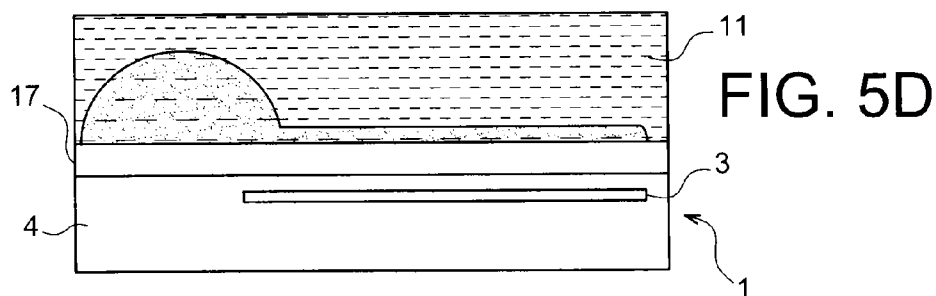
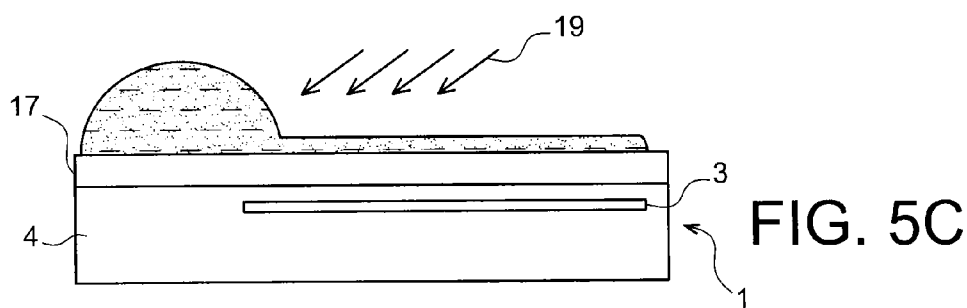
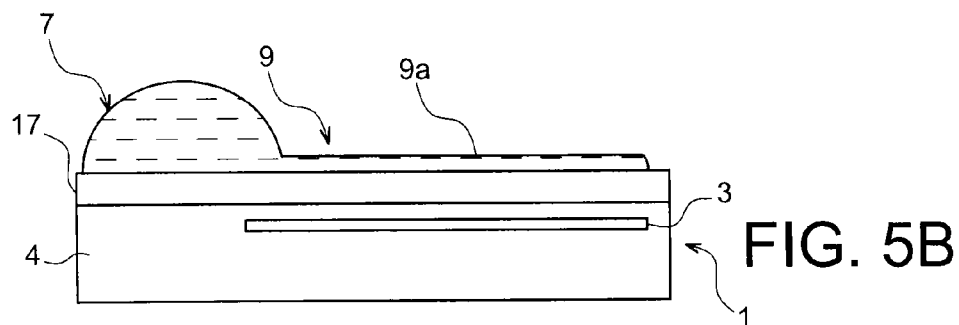
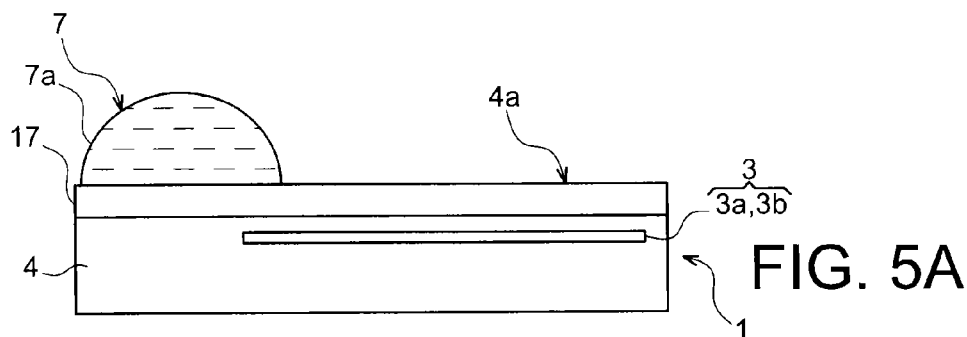


FIG. 4



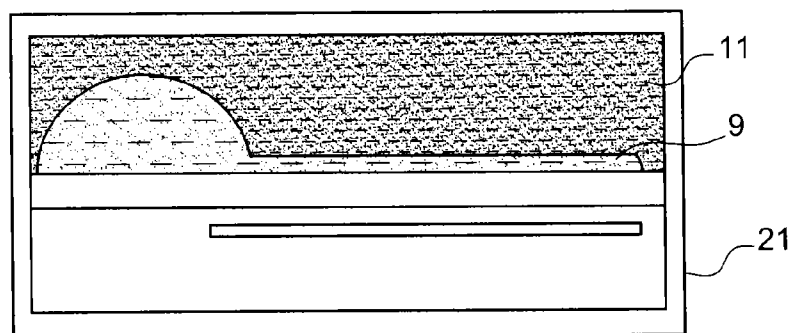


FIG. 5E

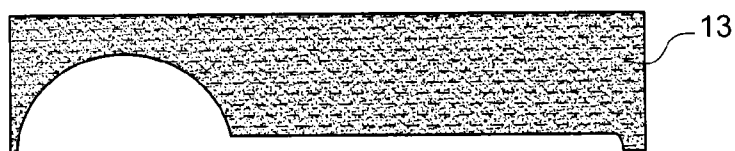


FIG. 5F

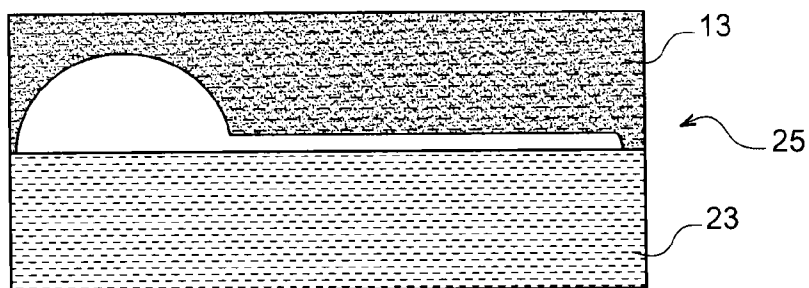


FIG. 5G

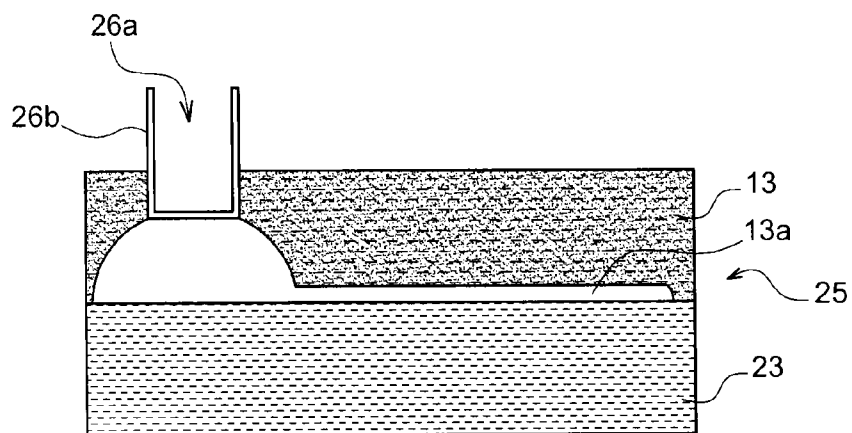


FIG. 5H

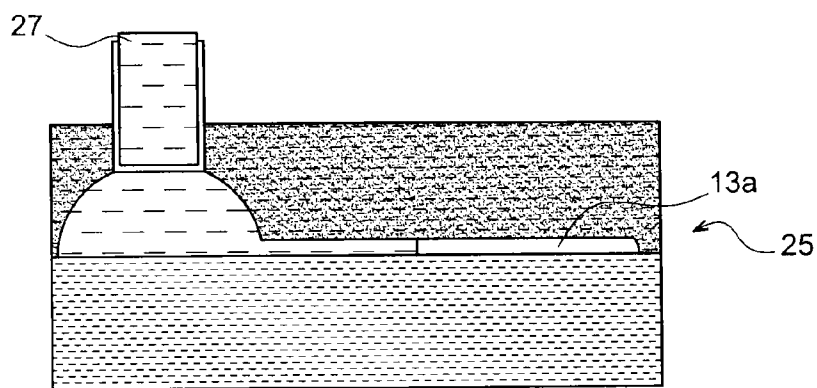


FIG. 5I

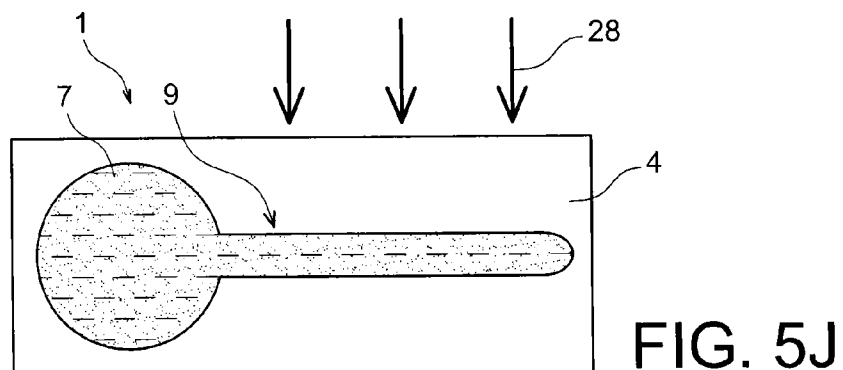


FIG. 5J

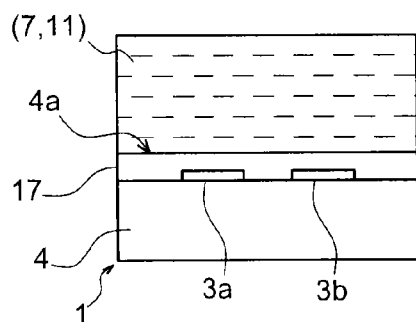


FIG. 6A

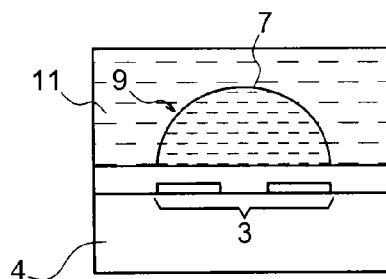


FIG. 6B

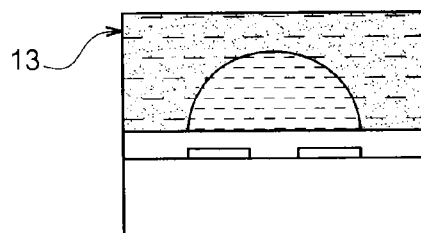


FIG. 6C



FIG. 6D

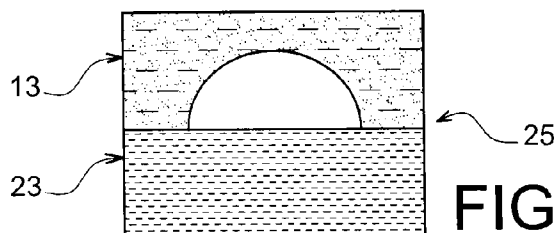


FIG. 6E

FORMATION OF A MICROFLUIDIC ARRAY

TECHNICAL FIELD

[0001] The present invention relates to the general field of microfluidics and, more particularly, the formation of microfluidic arrays comprising channels of half-round section.

PRIOR ART

[0002] In numerous fields, it is sought to manipulate and analyse liquid samples of small volume the least intrusively and as simply as possible. This may be the case, for example, to establish biological and/or chemical interactions between solutions for chemical analysis, biological or medical diagnosis, or instead in the field of genetic engineering or food processing.

[0003] In these fields, in general a flow of liquids is manipulated in microfluidic components comprising channels and chambers, using actuators external to the components, of pump, pressure controller or syringe driver type.

[0004] This type of component generally implements a technology of MEMS type. The channels are formed by assembly of two plates, with at least one of the two etched and structured for example by photolithography to form the desired grooves.

[0005] According to another technology, less relevant because of the much lower resolution, the channels are formed by micro-machining on a PMMA type plastic card then covered with a cover.

[0006] The channels may also be formed by pouring cross-linking materials of PDMS type onto moulds machined beforehand by the aforementioned methods.

[0007] In all of these known devices, the geometry of the fluidic array is defined at conception. Moreover, their manufacture requires white room type equipment involving important means and manufacturing times. For a new geometry of components, it is thus necessary to carry out a new long and costly cycle of conception and formation.

[0008] Patent application WO2009/130274 of the applicant resolves this problem by proposing a method of manufacturing microfluidic channels, in a programmable and reconfigurable manner, using EWOD (ElectroWetting On Dielectric) displacement techniques or by LDEP (Liquid DiElectroPhoresis). More particularly, two non-miscible fluids, one of which could be solidified, are introduced between two plates provided with electrodes. One of the fluids is displaced according to the EWOD or LDEP technique and when the desired channels are formed, the phenomenon of hardening is activated to congeal the formation of these fluidic channels. The section of the channels manufactured by this method is rectangular.

[0009] Nevertheless, channels with rounded or semi-circular section are particularly useful for example in the manufacture of microfluidic pumps as described for example in the article of Unger et al., "Monolithic microfabricated valves and pumps by multilayer soft lithography", Science vol. 288: 113-116 (2000).

[0010] However, it is difficult to implement a controlled and reproducible method to form hemispherical structures. To form channels of rounded section, a technique exists described for example by Unger et al., in the document entitled "Monolithic Microfabricated Valves and Pumps by Multilayer Soft Lithography", Science 288: 113-116 (2000). This technique consists in using firstly the photolithography

method for etching grooves on a resin substrate. Then, an additional step known as "resin creep" is used to soften the resin and deform it at the level of the edges of the desired channels, so as to obtain more rounded channels.

[0011] Nevertheless, resin creep is a step difficult to control, long, and requires an optimisation for each thickness of resin and for each type of resin. The thickness of resin is often limited to several tens of μm (often 10 μm) because it is a micro-manufacturing step, not developed as the basis for this application and for these orders of magnitude. In addition, it is difficult to control exactly the heights of the channels formed from this technique, and even more difficult to intentionally vary the height of the channels on a same substrate. The desired dimensions (height and width) of the channels are also very limited through this technique. Thus, the creep technique is difficult to control and is not reproducible at all the desired channel dimensions. Moreover, the resins are viscous and thus the shape of the channels is more patatoid than semi-circular section.

[0012] The aim of the present invention is to overcome the aforementioned drawbacks by proposing a simple and precise method for the manufacture of microfluidic channels of semi-circular section, in a programmable and reconfigurable manner.

DESCRIPTION OF THE INVENTION

[0013] The subject matter of the invention is a method of forming a microfluidic array comprising at least one channel of semi-circular section, comprising the following steps:

[0014] bringing into contact a first liquid with an array of electrodes of a microfluidic chip comprising at least one pair of substantially parallel and coplanar electrodes arranged on a substrate,

[0015] activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure comprising at least one fluidic finger, and

[0016] using said fluidic structure as a mould to form said microfluidic array by solidification or hardening of a second liquid deposited on the microfluidic chip and hugging the shape of said fluidic structure.

[0017] Thus, the method uses the technique of liquid dielectrophoresis LDEP in an open configuration to generate in a rapid manner fluidic fingers of semi-circular section. In fact, the sections of the fluidic fingers are naturally semi-circular because the electric field constrains the first liquid to go towards the gap separating the two electrodes. In addition, the dimensions (height and width) of these fluidic fingers can vary over a very wide range extending from several hundreds of nanometres to several hundreds of micrometres. The fluidic fingers are then used to form by moulding, in a simple, reproducible, programmable and reconfigurable manner, microfluidic arrays comprising channels of hemispherical section.

[0018] According to a first embodiment, said first liquid has a property of hardening and said method comprises the following steps:

[0019] hardening said first liquid materialising said fluidic structure while maintaining the array of electrodes in activation during the step of hardening in order to congeal said fluidic structure, and

[0020] flowing the second liquid onto said congealed fluidic structure.

[0021] According to this first embodiment, the fluidic structure is congealed before the introduction of the second

liquid thereby avoiding any interaction between the two liquids and forming a structural mould of high precision making it possible for example to form in a simple manner a plurality of identical microfluidic arrays without the necessity of restarting the process of actuation of the first liquid.

[0022] Advantageously, the first liquid is a liquid-solid phase change material selected from the following materials: epoxy, silicone or resin based adhesive, UV adhesive, gel, cross-linking polymer, paraffin, agarose, gelatine, beeswax, and wax.

[0023] Thus, the first liquid may be selected from a wide choice of phase change materials at a temperature comprised for example between 0° C. and 150° C.

[0024] Advantageously, the first liquid is a UV adhesive and the hardening of said first liquid is carried out by exposure to UV radiation at a wavelength adapted to the cross-linking wavelength of said UV adhesive.

[0025] Thus, the fluidic structure may be congealed at a distance and in a simple and rapid manner without resorting to a heat source.

[0026] Advantageously, the method comprises a step of melting the hardened or solidified material of said first liquid in order to reconfigure the fluidic structure.

[0027] Thus, by inverting the hardening process the method may be restarted by re-using the microfluidic chip to form a fluidic structure having a different geometry.

[0028] According to a second embodiment, the second liquid is non-miscible with the first liquid such that the interface between the two liquids takes the shape of said fluidic structure under the effect of the activation of said array of electrodes, the first liquid being covered with the second liquid.

[0029] According to this second embodiment, the interface between the two non-miscible liquids is advantageously used as an impression which is materialised by the hardening of the second liquid thereby forming in a simple manner the microfluidic array.

[0030] Advantageously, the first liquid is deionised water, water, an organic liquid, a solvent, or an aqueous solution.

[0031] Thus, a liquid is used for which the actuation by the LDEP technique does not require an activation at high frequency and which can then be easily evacuated after the hardening of the second liquid.

[0032] Advantageously, the second liquid is a liquid-solid phase change material selected from the following materials: cross-linking polymers, paraffin, agarose, gelatine, beeswax, wax, epoxy, silicone or resin based adhesive, UV adhesive, and gel.

[0033] Thus, the second liquid may be selected from a wide choice of phase change materials to form microfluidic arrays of high quality.

[0034] Advantageously, the geometry of the microfluidic array is programmable by the activation of the electrodes in an independent manner. Thus, from a single microfluidic chip, it is possible to form a plurality of fluidic arrays having different geometries.

[0035] Advantageously, the shape and/or the dimensions of said at least one fluidic finger of the microfluidic array is configurable depending on the shape and/or the width and/or the number of electrodes. Thus, fluidic channels of any shape, width, or height may be formed.

[0036] Advantageously, in the course of a same actuation by liquid dielectrophoresis, said at least one fluidic finger may be formed with variable dimensions. Thus, with a same LDEP

actuation, it is possible to form fluidic channels comprising different zones having different lengths and/or depths and/or widths.

[0037] Advantageously, said microfluidic array is used as a model plate to form other microfluidic arrays.

[0038] Thus, the microfluidic array may be used for the manufacture of a mould in order to form in a simple manner a plurality of identical fluidic arrays.

[0039] The invention targets a method of forming a microfluidic array comprising at least one channel of semi-circular section, comprising the following steps:

[0040] placing a mother drop of a first liquid having a property of hardening on an initial position of an array of electrodes comprising at least one pair of substantially parallel and coplanar electrodes arranged on a substrate of a microfluidic chip,

[0041] activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure comprising at least one fluidic finger,

[0042] hardening said first liquid materialising said fluidic structure while maintaining the array of electrodes in activation in order to congeal said fluidic structure,

[0043] flowing a second liquid onto the microfluidic chip covering said congealed fluidic structure,

[0044] hardening the second liquid to form the microfluidic array, and

[0045] removing the microfluidic array from the mould.

[0046] The invention also relates to a method of forming a microfluidic array comprising at least one channel of semi-circular section, comprising the following steps:

[0047] placing the non-miscible first and second liquids on a free surface of a microfluidic chip comprising an array of electrodes having at least one pair of substantially parallel and coplanar electrodes, the second liquid having a property of hardening,

[0048] activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure comprising at least one fluidic finger, the interface between the first and second liquids taking the shape of said fluidic structure,

[0049] hardening said second liquid covering said fluidic structure while maintaining the array of electrodes in activation such that the impression of the fluidic structure is found in the second hardened liquid thereby forming the fluidic array, and

[0050] disbonding the microfluidic array from the microfluidic chip.

[0051] Advantageously, the method comprises the following steps:

[0052] assembling the microfluidic array to a support to form a microfluidic component, and

[0053] forming at least one hole in said assembly to create a fluidic input.

[0054] The invention also relates to a microfluidic device comprising a microfluidic array formed according to any of the preceding characteristics.

[0055] Other advantages and characteristics of the invention will become clear from the detailed non-limiting description given below.

BRIEF DESCRIPTION OF DRAWINGS

[0056] Embodiments of the invention will now be described, by way of non-limiting examples, while referring to the appended drawings, in which:

[0057] FIGS. 1A-1G illustrate schematically a method of forming a microfluidic array, according to the invention;

[0058] FIGS. 2A-2F illustrate schematically the formation of a fluidic structure on an array of digitalised electrodes, according to the invention;

[0059] FIGS. 3A-3C illustrate schematically the formation of a fluidic structure on an array of electrodes in continuous configuration, according to the invention;

[0060] FIG. 4 illustrates schematically an example of a microfluidic chip for the formation of a microfluidic array, according to the invention;

[0061] FIGS. 5A-5J illustrate schematically a method of forming a microfluidic array, according to a first embodiment of the invention, with reference to a longitudinal section of the microfluidic chip of FIG. 4;

[0062] FIGS. 6A-6E illustrate schematically a method of forming a microfluidic array, according to a second embodiment of the invention, with reference to a transversal section of the microfluidic chip of FIG. 4.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0063] The principle of the invention is to take advantage of the actuation of a liquid by dielectrophoresis LDEP in an open configuration to mould microfluidic arrays comprising channels of semi-circular section.

[0064] FIGS. 1A-1G illustrate schematically a method of forming a microfluidic array, according to the invention.

[0065] More particularly, FIG. 1A represents, in section, a microfluidic chip 1 comprising an array of electrodes 3 arranged on a substrate 4. The array of electrodes 3 comprises at least one pair of substantially parallel and coplanar displacement electrodes 3a, 3b. FIG. 1B represents a top view of the microfluidic chip, according to a scale smaller than that of FIG. 1A.

[0066] Pair of electrodes is taken to mean either a pair of continuous electrodes, extending along a given path (see FIGS. 3A-3C), or a plurality of adjacent elementary electrodes (see FIGS. 2A-2E). In this latter case, each electrode is separated from its neighbour by a small spacing, comprised between the tenth of the width of the electrode and two times the width of the electrode.

[0067] The array of electrodes 3 is moreover connected to an electrical interface 5 making it possible to apply potential differences between the electrodes 3a, 3b. The array of electrodes 3 is thereby configured to form by liquid dielectrophoresis LDEP, under the effect of an electrical activation, at least one fluidic finger along the activated electrodes.

[0068] Liquid dielectrophoresis LDEP is taken to mean the application of an electrical force, generated by an oscillating non uniform electric field, on a liquid. The formation of a fluidic finger by liquid dielectrophoresis is especially described in the article of Jones entitled "Liquid dielectrophoresis on the microscale", J. Electrostat, 51-52 (2001), 290-299. When the liquid is situated in an electric field, the molecules of the liquid acquire a non-zero dipole and are polarised. In so far as the field is non uniform, a Coulomb force appears and induces the displacement of the molecules of the liquid, and thus all of the liquid, towards a field maximum. The liquid is then naturally constrained by the electric field to have a semi-circular section.

[0069] FIG. 1C is a top view representing a bringing into contact of a first liquid 7 more or less electrically insulating, with the array of electrodes 3. More particularly, the first

liquid 7 corresponds to a mother drop, of important volume, situated upstream of the fluidic path. It will be noted that when the first liquid 7 is not electrically insulating, it is advantageous to add onto the substrate a passivation dielectric layer (see FIG. 4) covering the electrodes in order to prevent any phenomenon of electrolysis. Preferably, the electrodes are covered with a layer of a hydrophobic material, such as SiOC, Teflon or Parylene, the thickness of the layer being for example comprised between 100 nm and 1 μ m. This hydrophobic layer is intended to enter into contact with the liquid manipulated by LDEP and makes it possible to obtain a drop of hemispheric shape. It is insulating. The hydrophobic layer is insulating and may be deposited on another insulating layer covering the electrodes (see FIG. 4), for example SiO₂, Si₃N₄, photolithography resin for example SU8. The thickness of this other insulating layer is comprised between 100 nm and 1 μ m and is intended to prevent a breakdown in the hydrophobic layer.

[0070] FIG. 1D is a sectional view and FIG. 1E is a top view representing the activation of the array of electrodes 3 by the application of an ac voltage. The frequency of the voltage is comprised between, for example, several hertz (for the least conductive liquids) and several megahertz, for example between 10 kHz and 10 MHz (for the most conductive liquids), and of a preferential voltage of several RMS volts to several hundreds of RMS volts. Usually, the frequency applied does not exceed several hundreds of kHz. When the liquid 7 is highly insulating, with for example a conductivity below 10^{-9} S·m⁻¹, the actuation threshold frequency is of the order of one Hz. The voltage may even be dc in the case of a highly insulating liquid.

[0071] Thus, under the effect of the electric field, the first liquid 7 is stretched by liquid dielectrophoresis to form a fluidic structure 9 comprising at least one fluidic finger 9a (see also FIGS. 2B-3C) and of semi-circular section along a path defined by the activated electrodes 3a, 3b.

[0072] FIG. 1F shows that the fluidic structure 9 is used as a mould to form the microfluidic array from a second liquid 11 deposited on the microfluidic chip 1 and hugging the shape of the fluidic structure 9. The second liquid 11 is a compound of a liquid-solid phase change material which may be a cross-linking polymer of PDMS type, a paraffin of C_nH_{2n+2} type, an agarose, a gelatine, a gel, a beeswax, an epoxy, silicone or resin based adhesive, or a UV adhesive.

[0073] Thus, the solidification (or hardening) of the second liquid 11 that forms the surrounding enclosure of the fluidic structure 9 generates a solid three-dimensional structure, the shape of which hugs the fluidic finger. In other words, the fluidic finger constitutes an impression or a mould, defining the shape of the second hardened liquid. At this stage, the electrical activation is stopped, which leads to the removal of the liquid finger whereas the solidified structure of the second liquid remains integrated. The latter then forms a microfluidic array 13 comprising at least one fluidic channel 13a of substantially semi-circular section, as illustrated in FIG. 1G. This array may be implemented in continuous microfluidic applications (i.e., not necessarily needing the actuation of an electrode to force a flow).

[0074] It will be noted that the microfluidic array 13 can also be used as a model plate to form other microfluidic arrays.

[0075] FIGS. 2A-2F illustrate schematically the formation of a fluidic structure on an array of digitalised electrodes, according to the invention.

[0076] FIG. 2A is a top view representing a microfluidic chip 1 on which is deposited a drop of liquid 7. According to this example, the microfluidic chip 1 comprises an array of electrodes 3 comprising a plurality of discontinuous or digitalised electrodes $3a, 3b, \dots, 3i, \dots, 3n$ in the form of pixels, arranged in a matrix, each pixel $3i$ of this matrix of electrodes being addressable independently of the other pixels. Thus, from a same two-dimensional array 3 of electrodes, and particularly of matrix type, it is possible to form a wide variety of microfluidic arrays with varied geometries. The denser the matrix of electrodes, the greater the geometric resolution of the channel and the greater the complexity of the fluidic array.

[0077] FIGS. 2B-2F give examples of geometry of fluidic arrays that may be formed on the same microfluidic chip represented in FIG. 2A.

[0078] The example of FIG. 2B shows the activation of a sub-set of pixels $3i$ forming a right angle path 31. The pixels $3i$ situated on the edge of the path 31 are connected to ground M whereas those situated on the other edge are traversed by a non-uniform voltage V. Generally speaking, the fluidic path extends along couples of coplanar pixels, each couple being constituted of an electrode and a counter-electrode, between which the potential varies.

[0079] FIG. 2C shows that the fluidic finger 9a derived from the mother drop extends along the path 31 defined by the sub-set of activated pixels $3i$. It will be noted that advantageously capillary effects mean that the angular shapes of the paths defined by the activated pixels $3i$ are going to result in rounded or curved shapes of the fluidic finger 9a. Thus, a fluidic array 13 may be formed while avoiding angular shapes which are sometimes undesirable in microfluidics.

[0080] Furthermore, FIG. 2D is a section along the plane AA' of FIG. 2C showing that the section of the fluidic finger is naturally semi-circular.

[0081] The example of FIG. 2E shows the formation of a fluidic finger 9a according to another path determined by the activation of another sub-set of pixels $3i$. The geometry (shape and dimensions) of the fluidic structure 9 may thus be easily programmable by activating the electrodes in an independent manner thereby making it possible to form a wide geometric variety of microfluidic arrays.

[0082] Thus, the present invention makes it possible to re-use the same microfluidic chip 1 to create moulds materialised by fluidic structures 9 of different geometric shapes.

[0083] It is also possible to control the heights of a fluidic finger 9a on a same microfluidic chip 1 by varying the number of activated electrodes $3i$. In fact, the example of FIG. 2F shows that the radius R of the circular section on a zone 91 of the fluidic finger 9a may be increased by activating additional pixels $3i$ on this zone 91.

[0084] Thus, the geometric shape and/or the dimensions of a fluidic finger 9a may be configurable as a function of the shape and/or the number of electrodes $3i$ activated and/or the width of the electrodes $3a, 3b$ (see also FIG. 3B).

[0085] Furthermore, FIGS. 3A-3C illustrate schematically the formation of a fluidic structure on an array of electrodes in continuous configuration, according to the invention.

[0086] In FIG. 3A is represented a microfluidic chip 1 comprising an array of electrodes 3 of particular geometry.

[0087] The array of electrodes 3 in continuous configuration may have complex shapes comprising for example coil shaped electrodes 33, electrodes having bends at right angles or cross-shaped 35, and electrodes of variable width 37.

[0088] The fluidic fingers derived from the mother drop extend along different paths determined by the pairs of activated electrodes. Then, it is possible to form in a simple manner and in a single operation channels of different dimensions and different shapes for practically all microfluidic applications. For example, it is possible to form a microfluidic array comprising a channel with a stage and/or a chamber and/or a convergent section and/or a divergent section and/or a constriction and/or a coil-shaped channel.

[0089] The example of FIG. 3B illustrates a pair of rectangular and coplanar electrodes $3a, 3b$ having a variable width. More particularly, the pair of electrodes $3a, 3b$ has a wide zone 34 formed of flat protuberances $3a1, 3b1$ which extend towards the exterior of each electrode $3a, 3b$. The protuberances $3a1, 3b1$ are arranged symmetrically with respect to one other and each belongs to a different electrode. It will be noted that the radius of the semi-circular section of the fluidic finger 9a which extends on the pair of electrodes is equal to the distance between the outer edges of the electrodes $3a, 3b$. The fluidic finger 9a then has a bigger radius at the level of the protuberances $3a1, 3b1$, as illustrated in FIG. 3C.

[0090] It is then possible to envisage different shapes and dimensions of fluidic fingers 9a by varying the number and the geometry of the electrodes $3i, 3a, 3b$. In particular, it is possible to vary the dimensions (lengths, heights, widths) of the fluidic fingers 9a in the course of a same LDEP actuation by activating electrodes $3a, 3b$ of variable widths (FIGS. 3B-3C) or by varying the number of activated electrodes $3i$ (FIG. 2E). Consequently, the dimensions of the channels on a same mould may be controlled.

[0091] It will be noted that, in the prior art, the heights of channels are defined by the methods and the associated etching times. Thus, to vary the height of a channel, the sole means was to go through several steps of photolithography requiring several masks, followed by several etching steps. In other words, a number N of different heights of channels required the manufacture of N photolithography masks, N photolithography steps and as many etching steps.

[0092] In FIG. 4 is represented a more detailed example of a microfluidic chip for the formation of a microfluidic array, according to the invention.

[0093] The microfluidic chip 1 comprises a substrate 4 having a free surface 4a. The material of the substrate 4 may be selected from the following materials: silicon, monocrystalline silicon, polycrystalline silicon, silicon nitride, silicon oxide, glass, Pyrex or an organic material such as polycarbonate or PEEK, plastic, paper, nickel, tungsten, platinum, etc. The thickness of the substrate 4 may be any thickness, comprised for example between several tens of microns and several millimetres.

[0094] The substrate 4 comprises a metal level for the definition of an array of electrodes 3 adapted to form by liquid dielectrophoresis fluidic fingers on the free surface 4a of the substrate. These electrodes $3a, 3b$ are impressions obtained by deposition then etching of a fine layer of a semi-conductor or of a metal which may be selected from aluminium, copper, gold, platinum, ITO (Indium Tin Oxide). The thickness of the electrodes $3a, 3b$ is from several tens of nm to several hundreds of nm, for example of the order of 200 nm.

[0095] The array of electrodes 3 comprises at least one pair of displacement electrodes $3a, 3b$ parallel and coplanar with each other, arranged at the level of the free surface 4a of the substrate 4. The structure of the electrodes makes it possible to define the zones where the electrophoresis forces are going

to act. The example of FIG. 4 illustrates a single pair of electrodes **3a**, **3b** of length for example of 1 mm to 2 mm.

[0096] The inner edges of a pair of electrodes are spaced apart by a distance g , for example of the order of 4 μm to 10 μm . Each electrode has a width noted w of the order of 8 μm to 20 μm and consequently, by noting $2R$ the distance separating the outer edges of the electrodes **3a**, **3b**, the radius R given by $R = (w + g)/2$ of the semi-circular section of the fluidic finger is then of the order of 10 μm to 25 μm . In fact, when the width w of the electrodes is of the same order of magnitude as their spacing g , the fluidic finger at all points of the path covers a zone inscribed between the two lateral ends of the electrodes. Thus, the dimensions of the channels formed by the fluidic fingers are of the order of 10 μm to 25 μm in terms of width and depth. It may also be envisaged to form channels, the dimensions (width, depth) of which are comprised between 1 μm (or even less than a micrometre) up to several hundreds of micrometres, for example 500 μm .

[0097] Moreover, the lengths of the fluidic fingers and consequently those of the channels can be very consequent. In fact, it is possible to form fluidic fingers by LDEP over lengths of several tens of millimetres. It is even possible to envisage forming fluidic fingers (and thus channels) of several tens of centimetres, as long as the input of liquid of the mother drop is conserved.

[0098] It should be noted that the formation of a fluidic finger is very rapid, with a displacement speed of the liquid of the order of 0.1 to 10 cm/s; only 50 to 500 ms suffices to form a fluidic finger of 5 mm.

[0099] After structuring the array of electrodes **3**, the substrate **4** may advantageously be covered with at least one passivation dielectric layer **17** in order to guard against risks of electrolysis of the first liquid if the latter is electrically conducting.

[0100] The passivation layer **17** may be an insulating layer for example, an oxide SiO_2 , a nitride (SiN , Si_3N_4), resins, dry films, SiOC , Teflon type hydrophobic polymers (registered trademark—tetra-fluoroethylene) or other fluoropolymers, a polymer of poly-p-xylylene (parylene), a high-k oxide deposited by a method known as ALD (HfO_2 , Al_2O_3 , ZrO_2 , SrTiO_3 , BaTiO_3 , $\text{Ba}_{(1-x)}\text{Sr}_x\text{TiO}_3$ (BST) . . .), and have a thickness comprised between several nm (for example 10 nm or 25 nm) and several microns (for example 5 μm). High-k oxides have a high dielectric permittivity, which makes it possible to increase the efficiency of the transduction. It makes it possible to avoid the electrolysis of the liquid if this was in direct contact with the array of electrodes **3**.

[0101] Preferably, the substrate **4** is covered with a double passivation layer: a first dielectric layer **17a** for example silicon nitride SiN (from 100 nm to 1 μm) and a second layer **17b** for example SiOC or Teflon (of 100 nm to 1 μm) for its hydrophobic properties forming the free surface **4a** of the substrate **4**. It will be noted that the hydrophobic layer enables the liquid to have a high contact angle in particular, greater than 90° .

[0102] Moreover, the array of electrodes **3** is connected to an electrical interface **5** comprising switching means **5a** and voltage generating means **5b** to activate the electrode array **3** according to the desired configuration.

[0103] FIGS. 5A-5J illustrate schematically a method of forming a microfluidic array, according to a first embodiment of the invention, with reference to a longitudinal section of the microfluidic chip of FIG. 4.

[0104] According to this first embodiment, the first liquid **7** has a property of hardening making it possible to congeal the fluidic structure **9** during the activation of the electrodes **3a**, **3b**.

[0105] As an example, the first liquid **7** is composed of a liquid-solid phase change material selected from the following materials: epoxy, silicone or resin based adhesive, UV adhesive, gel (especially alginate or agarose), cross-linking polymer for example of PDMS type, paraffin of C_{n+2} type, gelatine, beeswax, wax.

[0106] According to a first step (FIG. 5A), a mother drop **7a** of around 1 μL of a first liquid **7**, for example a UV adhesive, is placed on the free surface **4a** of the substrate **4** at the level of the array of electrodes **3**. More particularly, the mother drop **7a** is placed on an initial position corresponding for example to the start of a pair of electrodes **3a**, **3b** of 1.5 mm length. It will be noted that, before hardening, the UV adhesive is sufficiently fluid, having for example a fluidity comprised between 1 centipoise and several hundreds of centipoises, to facilitate its actuation by LDEP.

[0107] Then, the array of electrodes **3** is activated by applying to it a voltage adapted to generate an oscillating and non-uniform electric field so as to actuate by LDEP the first liquid **7**. Thus, a fluidic structure **9** (FIG. 5B) comprising at least one fluidic finger **9a** of semi-circular section is formed on the array of electrodes **3**.

[0108] In fact, the example of FIG. 5B shows that when a sinusoidal voltage of amplitude 500 V and frequency 50 kHz is applied between the electrodes **3a**, **3b**, a fluidic finger **9a** (of UV adhesive) of semi-circular section extends over a very short time (of the order of a second) along the pair of electrodes **3a**, **3b**. The fluidic finger **9a** covers substantially the pair of electrodes **3a**, **3b** over their whole length, and has a contact width substantially equal to the distance $2R$ defined previously and corresponding to the distance separating the outer edges of the two electrodes **3a**, **3b**.

[0109] Then, after the formation of the fluidic structure **9**, a process of hardening or solidification of the first liquid **7** is carried out materialising the fluidic structure **9** while maintaining the array of electrodes **3** in activation in order to congeal the fluidic structure **9**. The process of hardening or solidification of the first liquid **7** may be carried out by a change of temperature, or by exposure to a specific radiation range depending on the material used for the first liquid **7**.

[0110] In fact, the example of FIG. 5C shows that after the displacement of the fluidic finger (of UV adhesive), the latter is exposed for at least one minute by the radiation **19** of a UV lamp (not represented) at a wavelength adapted to the cross-linking wavelength of the UV adhesive. After the hardening of the first liquid **7**, the UV lamp is switched off and the power supply to the electrodes **3** is cut. The fluidic finger **9a** is henceforth completely solid and plays the role of mould to manufacture a fluidic channel.

[0111] In fact, as soon as the fluidic structure **9** is formed and hardened, the second liquid **11** for example PDMS is poured (FIG. 5D) onto the microfluidic chip **1**, covering the congealed fluidic structure **9**.

[0112] Then, a process of hardening or solidification of the second liquid **11** is carried out by change of temperature, drying, or radiation (according to the material used) to form the microfluidic array.

[0113] The example of FIG. 5E shows that the assembly of the microfluidic chip **1** and of the second liquid **11** covering the congealed fluidic structure **9** is placed in an oven **21** for,

for example, one hour at 80° C. to replicate the PDMS material of the second liquid. In a variant, the assembly may be placed in the open air for 24 h. The impression of the structure 9 made of congealed UV adhesive is thus replicated in the cross-linked PDMS.

[0114] The example of FIG. 5F shows the microfluidic array 13 made of cross-linked PDMS after removing from the mould or disbonding from the microfluidic chip 1.

[0115] Then, FIG. 5G shows that the microfluidic array 13 made of cross-linked PDMS is assembled to another support 23, for example another cross-linked PDMS support with smooth surface to form a microfluidic component 25. The assembly is formed for example using an O₂ plasma, followed by placing in an oven for 2 h at 60° C.

[0116] FIG. 5H shows the formation of a hole in the assembly of the microfluidic component for example at the level of the initial position of the mother drop to create a fluidic input 26a. A capillary 26b is inserted into this hole, the capillary 26 then being able to be connected to a syringe driver, a pressure controller, a valve or any other fluidic equipment (not represented).

[0117] The example of FIG. 5I shows the filling of the fluidic channel 13a with a liquid of interest 27 via the fluidic input 26a.

[0118] Advantageously, the moulds can be reconfigured an unlimited number of times as long as the fluidic actuations can be carried out, in other words, as long as the array of electrodes 3 and the potential passivation layer 17 are not damaged. In fact, the phenomena of hardening (for, for example, the UV adhesive) or solidification (for, for example, paraffin) are reversible. It is possible for example to liquefy the paraffin by heating it and the UV adhesive may be dissolved with a stripping solution (for example, acetone or piranha) and thereby reconfigure the microfluidic array 13, creating a new array different from the first.

[0119] The example of FIG. 5J shows the stripping or washing 28 with acetone, of the mould made of UV adhesive hardened (i.e., the congealed fluidic structure 9) constituted beforehand in order to form another mould in accordance with what has been described above, in the same configuration of channels or in a different configuration of channels.

[0120] FIGS. 6A-6E illustrate schematically a method of forming a microfluidic array, according to a second embodiment of the invention, with reference to a transversal section of the microfluidic chip of FIG. 4.

[0121] According to this second embodiment, the second liquid 11 is non-miscible with the first liquid 7 such that the interface between the two liquids takes the shape of the fluidic structure 9 during the actuation of the first liquid 7 by LDEP.

[0122] As an example, the first liquid 7 is water, deionised water DIW, an organic liquid (for example oil), an aqueous solution or a solvent of ethanol, acetone, or glycerol type. The second liquid 11 is made of material having a property of hardening or solidification and preferably, a second liquid is chosen with a dielectric permittivity quite different to that of the first liquid in order that the actuation of the first liquid 7 by LDEP is optimal.

[0123] According to a first step, the first and second non-miscible liquids 7, 11 are placed on the free surface 4a of the substrate 4. As an example, firstly a bath of the second liquid 11 (for example, paraffin) is formed on the microfluidic chip 1 (FIG. 6A) and then, the first liquid 7 (for example, water) is placed or injected into said bath.

[0124] Then, the array of electrodes 3 is activated by applying thereto a voltage adapted to generate an oscillating and non-uniform electric field so as to actuate by LDEP the first liquid 7. More specifically, the interface between the two liquids is shaped by the liquid dielectrophoresis forces actuating the displacement of the first liquid 7 on the path defined by the activated electrodes 3a, 3b. Thus, the interface between the first and second liquids 7, 11 takes the shape of the fluidic structure 9 formed by the first liquid 7.

[0125] When the geometry of the desired fluidic structure 9 has been formed, the second liquid 11 covering the fluidic structure 9 is congealed by a process of hardening, solidification or phase change while maintaining the array of electrodes 3 in activation. The material of the second liquid 11 is thus going to memorise the shape of the fluidic structure 9 or, in other words, the impression of the fluidic structure 9 is going to be replicated in the material of the second hardened liquid 11 thereby forming the fluidic array 13 (FIG. 6C).

[0126] Then, the solidified or hardened microfluidic array 13 is disbonded from the microfluidic chip 1 (FIG. 6D).

[0127] FIG. 6E shows that the microfluidic array 13 is assembled to another support 23 to form a microfluidic component 25. Then, one or more holes may be made in the assembly of the microfluidic component to create a microfluidic device with one or more fluidic inputs.

[0128] The method according to the invention thus makes it possible to manufacture microfluidic devices for all applications that use microfluidics. Among these applications, may particularly be cited the manufacture of "Quake" peristaltic pumps or valves because channels with semi-circular section are practically indispensable for addressing this type of application.

[0129] Moreover, it will be noted that the invention may be used to conduct rapid prototyping with microfluidic chips made of PDMS, to address for example all biological and chemical applications.

[0130] Obviously, various modifications may be made by those skilled in the art to the invention that has been described, uniquely by way on non-limiting examples.

1. Method of forming a microfluidic array comprising at least one channel of semi-circular section, characterised in that it comprises the following steps:

bringing into contact a first liquid (7) with an array of electrodes (3) of a microfluidic chip (1) comprising at least one pair of substantially parallel and coplanar electrodes (3a, 3b) arranged on a substrate (4),

activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure (9) comprising at least one fluidic finger (9a), and

using said fluidic structure as a mould to form said microfluidic array by solidification or hardening of a second liquid (11) deposited on the microfluidic chip and hugging the shape of said fluidic structure.

2. Method according to claim 1, characterised in that said first liquid (7) has a property of hardening and in that said method comprises the following steps:

hardening said first liquid materialising said fluidic structure (9) while maintaining the array of electrodes (3) in activation during the step of hardening in order to congeal said fluidic structure, and

flowing the second liquid (11) onto said congealed fluidic structure.

3. Method according to claim 2, characterised in that the first liquid (7) is a liquid-solid phase change material selected from the following materials: epoxy, silicone or resin based adhesive, UV adhesive, gel, cross-linking polymer, paraffin, agarose, gelatine, beeswax, and wax.

4. Method according to claim 3, characterised in that the first liquid (7) is a UV adhesive and in that the hardening of said first liquid is carried out by exposure to UV radiation at a wavelength adapted to the cross-linking wavelength of said UV adhesive.

5. Method according to claim 4, characterised in that it comprises a step of melting the hardened or solidified material of said first liquid in order to reconfigure the fluidic structure.

6. Method according to claim 1, characterised in that the second liquid (11) is not miscible with the first liquid (7) such that the interface between the two liquids takes the shape of said fluidic structure (9) under the effect of the activation of said array of electrodes, the first liquid being covered with the second liquid.

7. Method according to claim 6, characterised in that the first liquid (7) is deionised water DIW, water, an organic liquid, a solvent, or an aqueous solution.

8. Method according to claim 1, characterised in that the second liquid (11) is a liquid-solid phase change material selected from the following materials: cross-linking polymers, paraffin, agarose, gelatine, beeswax, wax, epoxy, silicone or resin based adhesive, UV adhesive, and gel.

9. Method according to claim 1, characterised in that the geometry of the microfluidic array is programmable by the activation of the electrodes in an independent manner.

10. Method according to claim 1, characterised in that the shape and/or the dimensions of said at least one fluidic finger (9a) of the microfluidic array is configurable depending on the shape and/or the width and/or the number of electrodes.

11. Method according to claim 1, characterised in that in the course of a same actuation by liquid dielectrophoresis, said at least one fluidic finger is able to be formed with variable dimensions.

12. Method according to claim 1, characterised in that said microfluidic array is used as a model plate to form other microfluidic arrays.

13. Method of forming a microfluidic array comprising at least one channel of semi-circular section, characterised in that it comprises the following steps:

placing a mother drop of a first liquid (7) having a property of hardening on an initial position of an array of electrodes (3) comprising at least one pair of substantially parallel and coplanar electrodes arranged on a substrate of a microfluidic chip,
activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure (9) comprising at least one fluidic finger,
hardening said first liquid materialising said fluidic structure while maintaining the array of electrodes in activation in order to congeal said fluidic structure,
flowing a second liquid (11) onto the microfluidic chip covering said congealed fluidic structure,
hardening the second liquid to form the microfluidic array, and
removing the microfluidic array from the mould.

14. Method of forming a microfluidic array comprising at least one channel of semi-circular section, characterised in that it comprises the following steps:

placing non-miscible first and second liquids (7, 11) on a free surface of a microfluidic chip comprising an array of electrodes (3) having at least one pair of substantially parallel and coplanar electrodes, the second liquid (11) having a property of hardening,

activating said array of electrodes so as to actuate by liquid dielectrophoresis LDEP said first liquid to form a fluidic structure comprising at least one fluidic finger (9a), the interface between the first and second liquids taking the shape of said fluidic structure,

hardening said second liquid covering said fluidic structure while maintaining the array of electrodes in activation such that the impression of the fluidic structure is replicated in the second hardened liquid thereby forming the fluidic array, and

disbonding the microfluidic array from the microfluidic chip.

15. Method of forming a microfluidic component using the microfluidic array formed according to claim 1, characterised in that it comprises the following steps:

assembling the microfluidic array (13) to a support (23) to form a microfluidic component (25), and

forming at least one hole (26a) in said assembly to create a fluidic input.

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