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(54) Ink jet recording apparatus.

(57) An inkjet recording apparatus comprises an inkjet head (10) having for each of one or more nozzles (4) an ink passage (7, 6) in communication with the nozzle (4) and an electrostatic actuator. The actuator includes a diaphragm (5) provided at one part (6) of the ink passage, a nozzle electrode (21) provided in opposition to the diaphragm (5) with a gap (G) in between and a vibration chamber (9) having upper and lower walls of which one wall is formed by one part of said diaphragm (5), while said nozzle electrode is attached to the other wall. The diaphragm constitutes one and the nozzle electrode (21) the other plate of a capacitor. Drive means selectively charge and discharge each actuator such as to displace its diaphragm (5) by electrostatic force, thereby to eject ink droplets from said one or more nozzles. Vibration chamber (9) is sealed to be airtight. Its volume V is such that the ratio between this volume V and the volume ΔV displaced by the diaphragm is within the range $2 \leqq V/\Delta V \leqq 8$. This enables sufficient electrostatic attraction with a sealed actuator and without necessity to increase the drive voltage.

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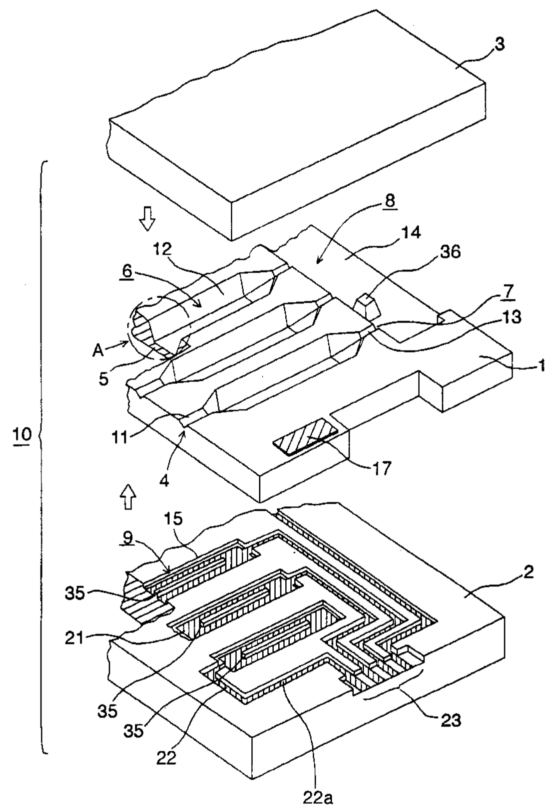

FIG. 1

The present invention relates to an inkjet recording apparatus and, more particularly, to an electrostatically driven inkjet head of the recording apparatus.

Inkjet recording apparatus having an inkjet head for ejecting ink droplets towards a recording medium in response to electric drive pulses are well known and commonly used. The inkjet head includes an actuator for converting each electric drive pulse into a pressure pulse whereby an ink droplet is ejected from a nozzle of the inkjet head. Inkjet heads in which the force of electrostatic attraction is used for the actuator are disclosed in, for example, JP-A-289351/1990, EP-A-0 580 283 and in EP-A-0 634 272, EP-A-0 629 502 and EP-A-0 629 503 (the latter three documents forming prior art according to Art. 54(3) EPC). An inkjet head in accordance with this art comprises one or more nozzles, a respective ink passage continuous to the or each nozzle, a diaphragm forming one plate of a capacitor and provided at one part of the or each ink passage, and a nozzle electrode located opposite to the diaphragm with an air gap in between. The nozzle electrode forms the other plate of the capacitor. An electrical pulse is applied between the diaphragm and nozzle electrode to deform the diaphragm by means of electrostatic force, thereby ejecting an ink droplet from the nozzle.

With these inkjet heads the actuator contains a vibration chamber formed between the diaphragm and nozzle electrode. When the vibration chamber is exposed to the open air, dust and other airborne particulate is attracted to the actuator's vibration chamber when the diaphragm is driven. As disclosed in EP-A-0 580 283 this problem can be corrected by sealing the actuator. However, when the actuator is sealed, air sealed inside the vibration chamber adds resistance to the electrostatic attraction of the diaphragm, and may inhibit sufficient electrostatic attraction for normal operation. When the electrostatic attraction of the vibration chamber decreases, insufficient pressure is generated to adequately eject ink, and print quality and reliability drop significantly. The decrease of electrostatic attraction can be compensated for by raising the drive voltage applied to the actuator. EP-A-0 580 283 discloses a drive voltage of 70 to 100 V. Such high drive voltage is undesirable, however.

Therefore, the object of the present invention is to provide an inkjet head whereby sufficient electrostatic attraction can be obtained even with a sealed actuator and with a drive voltage no higher than about 45 V.

This object is achieved with an inkjet recording apparatus as claimed in claim 1.

Preferred embodiments of the invention are subject-matter of the dependent claims.

In an inkjet head of the present invention the vibration chamber in the actuator is an airtight structure, thereby eliminating the possibility of foreign matter such as airborne particulate being attracted to and penetrating the vibration chamber when the diaphragm vibrates.

The inventors found out that in practice, the pressure increase inside the vibration chamber is sufficiently low not to prevent distortion of the diaphragm by electrostatic attraction, when the volume V of the sealed vibration chamber (hereinafter referred to as "actuator volume") is two or more times greater than the volume ΔV displaced by that diaphragm distortion that is necessary to ensure reliable ink ejection (hereinafter referred to as "displacement volume"). Thus, according to the present invention sufficient diaphragm distortion can be obtained without requiring an undesirably high drive voltage.

The upper limit for the ratio $V/\Delta V$ is determined such as to avoid an unnecessary increase of the inkjet head to obtain a high wafer yield (the number of heads made from one wafer) on the other hand.

It is possible to minimize the volume of the vibration chamber itself when a volume provided for accommodating a wiring member connecting the nozzle electrode to a terminal member is made to communicate with the vibration chamber and, thus, adds to the actuator volume. In this way a suitable actuator volume can be obtained without requiring enlargement of the inkjet head.

Sparking and actuator deterioration due to sparking can be prevented by sealing an inert gas, nitrogen gas, or dry air in the actuator or vibration chamber.

The invention will be described in more detail below with reference to the drawings which illustrate a referred embodiments only and in which:

- Fig. 1 is a partially exploded view of an inkjet head according to a preferred embodiment of the present invention;
- Fig. 2 is an enlarged view of portion A in Fig. 1;
- Fig. 3 is a lateral cross section of a complete assembled inkjet head according to the preferred embodiment of the present invention;
- Fig. 4 is a perspective view of the assembled inkjet head;
- Fig. 5 is a plan view taken along line A-A in Fig. 3; and
- Fig. 6 is used to describe the operation of the diaphragm.

The embodiment of the invention described below is an edge type inkjet head wherein ink droplets are ejected from nozzles provided at the edge of a substrate. It is to be noted that the invention may also be applied to a face type inkjet head wherein the ink is ejected from nozzles provided on the top surface of the substrate.

The inkjet head 10 of this embodiment is made up of three substrates 1, 2, 3 one stacked upon the other and structured as described in detail below. A first substrate 1 is sandwiched between second and third substrates 2 and 3, and is made from a silicon wafer. Multiple nozzles 4 are formed between the first and the third substrate by means of corresponding nozzle grooves 11 provided in the top surface of the first substrate 1 such as to extend substantially in parallel at equal intervals from one edge of the substrate. The end of each nozzle groove opposite said one edge opens into a respective recess 12. Each recess in turn is connected via a respective narrow groove 13 to a recess 14. In the assembled state the recess 14 constitutes a common ink cavity 8 communicating with the nozzles 4 via orifices 7 formed by the narrow grooves 13 and ejection chambers 6 formed by the recesses 12. As shown in Figs. 1 and 3, recess 14 has an ink supply opening at the rear side (side remote from the nozzles). The bottom of each ejection chamber 6 comprises a diaphragm 5 formed integrally with the substrate 1. As will be understood, the grooves and recesses referred to above can be easily and precisely formed by photolithographic etching of the semiconductor substrate. Note that diaphragms 5 are formed by first doping substrate 1 with boron to provide for etch stopping followed by etching to form the diaphragms with a thin, uniform thickness.

Electrostatic actuators each comprising a diaphragm and an associated nozzle electrode are formed between the first and the second substrate. A common electrode 17 of the actuators is provided on the first substrate 1. The magnitude of the work function of the semiconductor forming the first substrate 1 and the metal used for the common electrode 17 are important factors determining the effect of electrode 17 on first substrate 1. The semiconductor material used in this embodiment has a resistivity of 8 - 12 Ωcm, and the common electrode 17 has in fact a two-layer structure made from platinum on a titanium base layer or gold on a chrome base layer. The base layer is provided mainly to improve the bonding strength between the substrate and the electrode. The present invention shall not be so limited, however, and various other material combinations may be used according to the characteristics of the semiconductor and electrode materials.

As shown in Fig. 2, a thin oxide film 24, approximately 1 μm thick, is formed on the entire surface of first substrate 1 except for the common electrode 17. This creates an insulation layer for preventing dielectric breakdown and shorting during inkjet head drive.

Borosilicate glass is used for the second substrate 2 bonded to the bottom surface of first substrate 1. A recess 15 for accommodating a respective nozzle electrode 21 is formed in the top of second substrate 2 below each diaphragm 5. When the second substrate 2 is bonded to the first substrate 1 vibration chambers 9 are formed at the positions of recesses 15 between each diaphragm 5 and the opposing nozzle electrode 21. A long, thin support member 35 is located in the middle of each recess 15. The purpose of the support member 35 is to provide for an additional support in case of very thin diapragms. Support members 35 are not required if sufficient rigidity (resilience) for ink ejection is obtained by forming diaphragm 5 with sufficient thickness. The height of the support members 35 may correspond to or be less the depth of the recesses.

In this embodiment, recesses 15 formed in the top surface of the second substrate 2 provide for gaps between the diaphragms and the respective electrodes 21. The length G (see Fig. 3; hereinafter the "gap length") of each gap is equal to the difference between the depth of recess 15 and the thickness of the electrode 21. It is to be noted that this recess can alternatively be formed in the bottom surface of the first substrate 1. In this preferred embodiment, the depth of recess 15 is 0.3 μm, and the pitch and width of nozzle grooves 11 are 0.2 mm and 80 μm, respectively.

As shown in Fig. 1, the wiring formed in the top surface of second substrate 2 comprises the nozzle electrodes 21 and lead members 22 connecting each nozzle electrode to a respective terminal member 23. As shown, the lead members are located in grooves 22a connecting to the recesses 15. The terminal members 23 are located in a corresponding recess formed at one edge of second substrate 2. All recesses and grooves accommodating this wiring are preferably formed with the same depth although this may not always be necessary. The wiring (nozzle electrodes 21, lead members 22 and terminal members 23) is formed by sputtering gold onto the second substrate 2 to a thickness of 0.1 μm. Nozzle electrodes 21 are formed at positions and with shapes respectively matching diaphragms 5. ITO or another conductive oxide film material may be used in place of gold in the formation of the electrodes 21, their lead members 22 and terminal members 23.

Borosilicate glass is also used for the third substrate 3. Nozzles 4, ejection chambers 6, orifices 7, and ink cavity 8 are formed by bonding third substrate 3 to the top surface of first substrate 1. Support member 36 in ink cavity 8 adds reinforcement to prevent collapsing recess 14 when first substrate 1 and third substrate 3 are bonded together.

First substrate 1 and second substrate 2 are anodically bonded at 270 ~ 400°C by applying a 500 ~ 800-V charge, and first substrate 1 and third substrate 3 are then bonded under the same conditions to assemble the inkjet head as shown in Fig. 3. After anodic bonding, the gap length G formed between diaphragm 5 and nozzle electrode 21 on second substrate 2 is 0.2 μm in this embodiment.

After the inkjet head is thus assembled, drive circuit 102 is connected by connecting flexible printed circuit (FPC) 101 between common electrode 17 and terminal members 23 of nozzle electrodes 21 as shown in Figs. 3 and 4. An anisotropic conductive film is used in this embodiment to bond leads 101 with electrodes 17 and 23.

In the preferred embodiment, nitrogen gas is injected into vibration chambers 9, which are then sealed airtight using an insulating sealing agent 30. Vibration chambers 9 are sealed near terminal members 23 in this embodiment, thus enclosing vibration chamber 9 and the volume of the lead member grooves within the "volume of the actuator" (this is described in greater detail below).

Ink supply tube 33 and ink supply vessel 32 are fit externally to the back of the inkjet head. Ink 103 is supplied from an ink tank (not shown in the figures) into first substrate 1 via ink supply tube 33, vessel 32 and the ink supply opening at the rear of ink cavity 8 to fill ink cavity 8 and ejection chambers 6. The ink in ejection chambers 6 becomes ink droplets 104 ejected from nozzles 4 and printed to recording paper 105 when inkjet head 10 is driven as shown in Fig. 3.

The present invention is characterized by thus sealing vibration chambers 9 within the actuator, and setting the volume V of the actuator such that the ratio between the actuator volume V and the volume ΔV displaced by a distortion of diaphragm 5 is within the range $2 \leqq V/\Delta V \leqq 8$.

Fig. 6 is used to describe the operation of diaphragm 5.

When a drive voltage is applied to an actuator, the capacitor comprising the nozzle electrode 21 and diaphragm 5 is charged, and the diaphragm 5 is attracted to electrode 21 by electrostatic force and distorted as shown Fig. 6. This deflection increases the volume of ejection chamber 6 and reduces the volume of vibration chamber 9 by the displacement volume ΔV. The reduced volume of the vibration chamber causes the pressure P_O in the vibration chamber to increase by a pressure increment ΔP to an increased pressure P_i. When the drive voltage is removed and the capacitor is discharged diaphragm 5 returns to its initial state (where diaphragm 5 and electrode 21 are in parallel) in a short time and part of the displacement volume ΔV is utilized for ink ejection. While the distortion of the diaphragm in response to the drive voltage is a function of time, unless otherwise specified, ΔV and ΔP as used in this specification refer to the respective maximum values, i.e. those immediately prior to removal of the drive voltage.

As will be appreciated, Fig. 6 shows the case without support member. When support members 35 are provided Fig. 6 could be regarded as showing only one half of the arrangement (w/2 instead of w), i.e. between one lateral egde of the diapragm and the support member 35, the other half between the support member and the other lateral edge being symmetrical. While the following discussion is based on the assumption that no support members are employed it applies in substantially the same way to the case of using support members.

As mentioned before, the lower limit for the ratio $V/\Delta V$ ensures that the pressure increment ΔP in the vibration chamber is sufficiently low. The reason for the upper limit of $V/\Delta V$ is described below. The values shown in Table 1 are the design values for inkjet heads of various printing resolutions.

In Table 1, head types (1) and (2) are edge ejection type inkjet heads using a (100) face silicon substrate for the first substrate 1. In head type (1), the actuator volume includes the volume of vibration chamber 9 only and does not include any volume related to the wiring (lead members and terminal members) connected to the electrode. In head type (2), the actuator is sealed near the electrode terminals (see Figs. 3 and 5), and the actuator volume includes the volume of the cavity formed by the lead member groove 22a (which functions as "dummy volume" to increase the actuator volume) in addition to the volume of vibration chamber 9, thereby reducing the pressure increment ΔP in the vibration chamber associated with the displacement volume ΔV. Head types (3), (4), and (5) are face ejection type inkjet heads using a (110) face silicon substrate for the first substrate 1 with the actuator volume similarly maximized by using the dummy volume inside the limited head size. Each of head types (1) ~ (5) functions sufficiently as an inkjet head, and is designed so as to maximize the yield from each wafer.

In the case of head type (1), for example, the $V/\Delta V$ ratio is 2.31, and the increased pressure P_i in the vibration chamber is 1.77 kgf/cm^2 (17.3 x 10^4 Pa). If a dummy volume is provided in this type of head without changing the head size, the $V/\Delta V$ ratio increases to 4.69 and the increased pressure P_i drops approximately 30% to 1.27 kgf/cm^2 (12.4 x 10^4 Pa) as shown in the type (2) head.

It is not possible to further reduce the increased pressure P_i in the vibration chamber without increasing the head size. This would decrease the yield per wafer and increase unit cost.

When the resolution is increased, i.e., the nozzles are arranged closer together, the displacement volume ΔV decreases, because the volume of each ink droplet ejected is smaller than in case of a low resolution head.

Furthermore, the more nozzles the head has, the larger the dummy volume becomes, and the $V/\Delta V$ ratio is therefore increased, because the area of the lead members 22 relative to the total head area increases.

For example, the area occupied by diaphragms is approximately 40% of the total area of head chip in the case of head types (1) and (2), but is approximately 25% in head types (3), (4), and (5). The ratio $V/\Delta V$ is $\leqq 8$ when the greatest possible dummy volume is used in these high resolution inkjet heads without sacrificing yield per wafer or inkjet head functionality.

It is not possible to obtain a $V/\Delta V$ ratio greater than 8 without increasing the head size, which would reduce the yield per wafer and increase unit cost. Furthermore, the reduction in pressure increment ΔP in the vibration chamber obtained with $V/\Delta V \leqq 8$ is sufficient, and a further increase in the $V/\Delta V$ ratio does not provide a significant further reduction of the pressure increment: for example, the increased pressure P_i declines from 1.15 kgf/cm^2 (11.3 x 10^4 Pa) to only about 1 kgf/cm^2 (9.8 x 10^4 Pa). Therefore, the rational range for the $V/\Delta V$ ratio considering inkjet heads of various resolutions is $2 \leqq V/\Delta V \leqq 8$.

It should be further noted that while the present embodiment described above is sealed with nitrogen gas inside, the sealed gas of the invention shall not be so limited, and may alternatively be any (a) inert gas (e.g., He, Ne), (b) nitrogen gas, or (c) dry air that is chemically stable and will not chemically react when the inkjet head is driven (during electrical discharge), causing the gas properties to change and corroding or damaging diaphragm 5 or individual electrode 21. The preferred order of selection for these sealed gases is (a), (b), and (c) considering these performance requirements, but is (c), (b), (a) considering cost. It therefore follows that (b), nitrogen gas, is the preferred selection overall with respect to both performance and cost considerations. These sealed gases also prevent sparking inside vibration chamber 9, and yield stable operation.

In order that all actuators of a multi-nozzle inkjet head have the same characteristic it is preferable that the respective actuator volumes are equalized. As will be understood from Fig. 1, while the volume of the vibration chambers can easily be made equal among all actuators, the individual lead members 22 have different lenghts. Therefore, when the dummy volume provided by grooves 22a accommodating the lead members 22 is included within the total actuator volume, these grooves should preferably be dimensioned such that despite their different lengths each provides the same dummy volume.

Table 1

V/ΔV ratio of ink jet head

Head gap G = 0.2 µm

Head type	Head specifications Resolution [dpi]	Nozzles [No.]	Ink vol. [µg/dot]	Size [mm]	Area [mm^2]	Yield 3"wafer [No.]	Diaphragm size width [mm]	length [mm]	ΔV [mm^3]	V [mm^3]	V/ΔV	P_i [$x9.8\cdot10^4$ Pa]
1. Edge ejection type 1	49.9	12	0,15	9x11	99	31	0.366	9	0.00035	0.00081	2.31	1,77
2. Edge ejection type 2	49.9	12	0.15	9x11	99	31	0.366	8	0.00035	0.00165	4,69	1,27
3. Face ejection type 1	90	12	0.15	9x9	81	37	0.262	6.7	0.00019	0.00135	7.20	1,18
4. Face ejection type 2	180	24	0.04	9x9.5	85,5	37	0.121	7.3	0.00009	0.00071	7.60	1.15
5. Face ejection type 3	360	48	0.04	9x18.5	163.5	17	0.051	17.4	0.00009	0.00069	7.40	1.16

Claims

1. An inkjet recording apparatus comprising;
an inkjet head (10) having for each of one or more nozzles (4),

an ink passage (7, 6) in communication with the nozzle (4), and

an electrostatic actuator comprising a diaphragm (5) provided at one part (6) of the ink passage, a nozzle electrode (21) provided in opposition to the diaphragm (5) with a gap (G) in between, said diaphragm constituting one and the nozzle electrode (21) the other plate of a capacitor, and a vibration chamber (9) having upper and lower walls of which one wall is formed by said diaphragm (5), while said nozzle electrode is attached to the other wall, and

drive means (102) for selectively charging and discharging each actuator such as to displace its diaphragm (5) by electrostatic force, thereby to eject ink droplets from said one or more nozzles,

wherein said vibration chamber (9) is sealed to be airtight with a volume V such that the ratio between the volume V and the volume ΔV displaced by the diaphragm when the displacement of the diaphragm has its maximum is within the range $2 \leqq V/\Delta V \leqq 8$.

2. The apparatus according to claim 1, wherein said volume V includes a volume formed by a cavity (22a) accommodating a wiring member (22) connected to the electrode (21).

3. The apparatus according to claim 1 or 2 comprising multiple nozzles wherein each of the actuators has substantially the same volume V.

4. The apparatus according to claim 1, 2 or 3, wherein the vibration chamber (9) or the vibration chamber (9) and the said cavity (22a) for accommodating the lead member (22), respectively, are filled with an inert gas, nitrogen gas, or dry air.

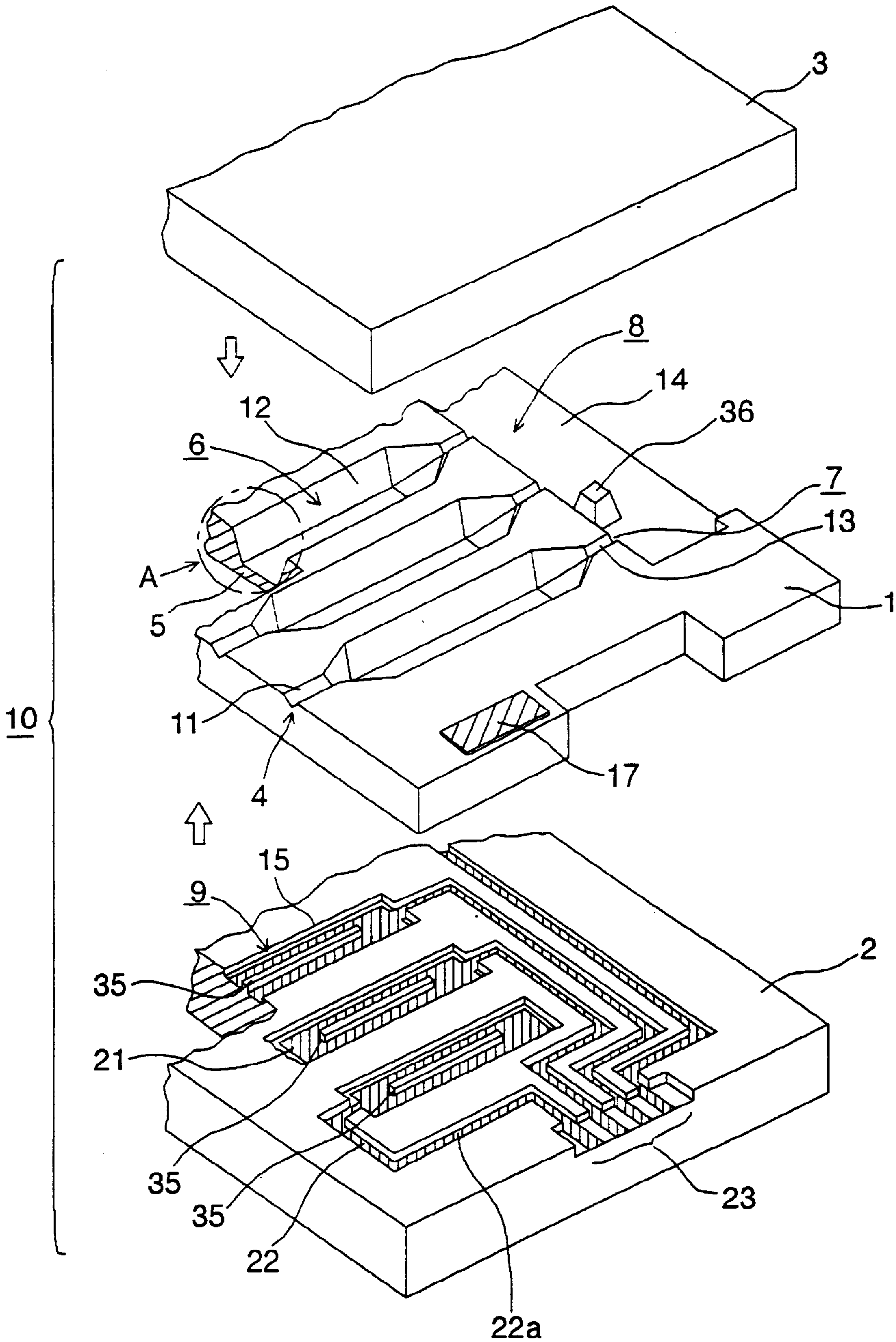

FIG. 1

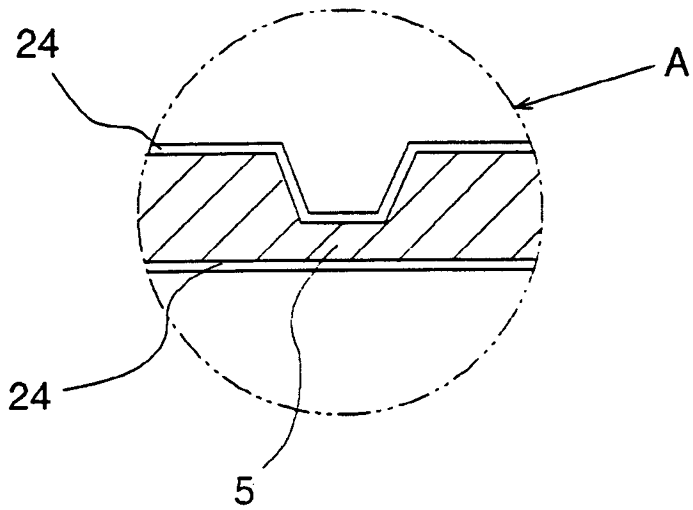

FIG. 2

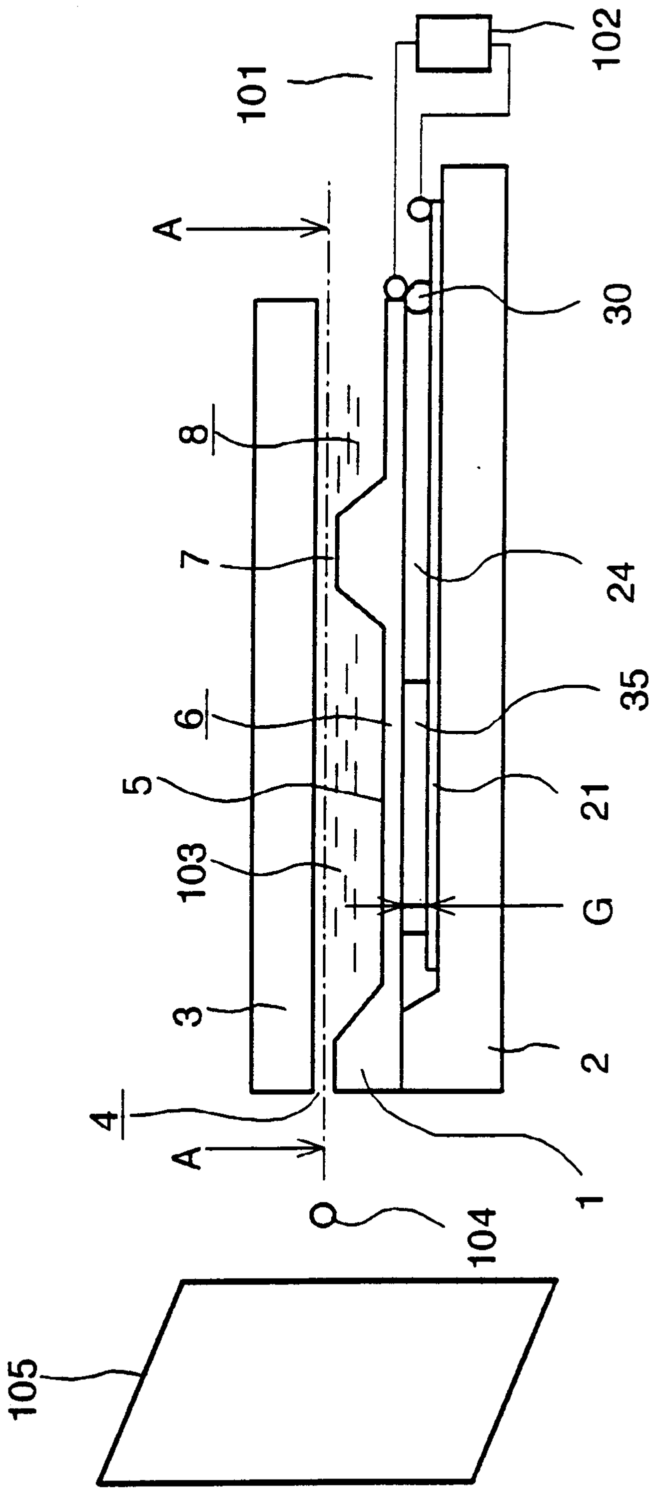

FIG. 3

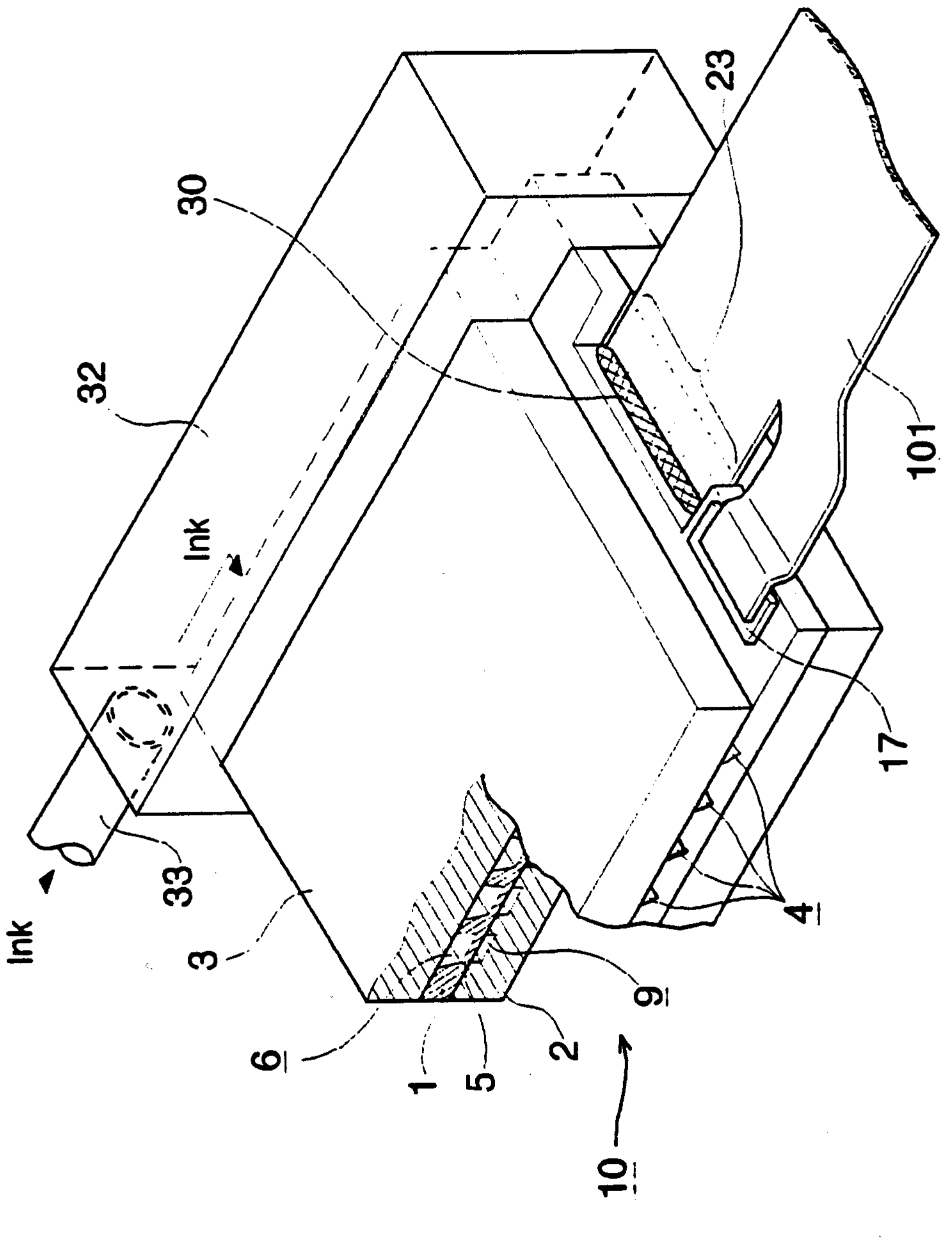

FIG. 4

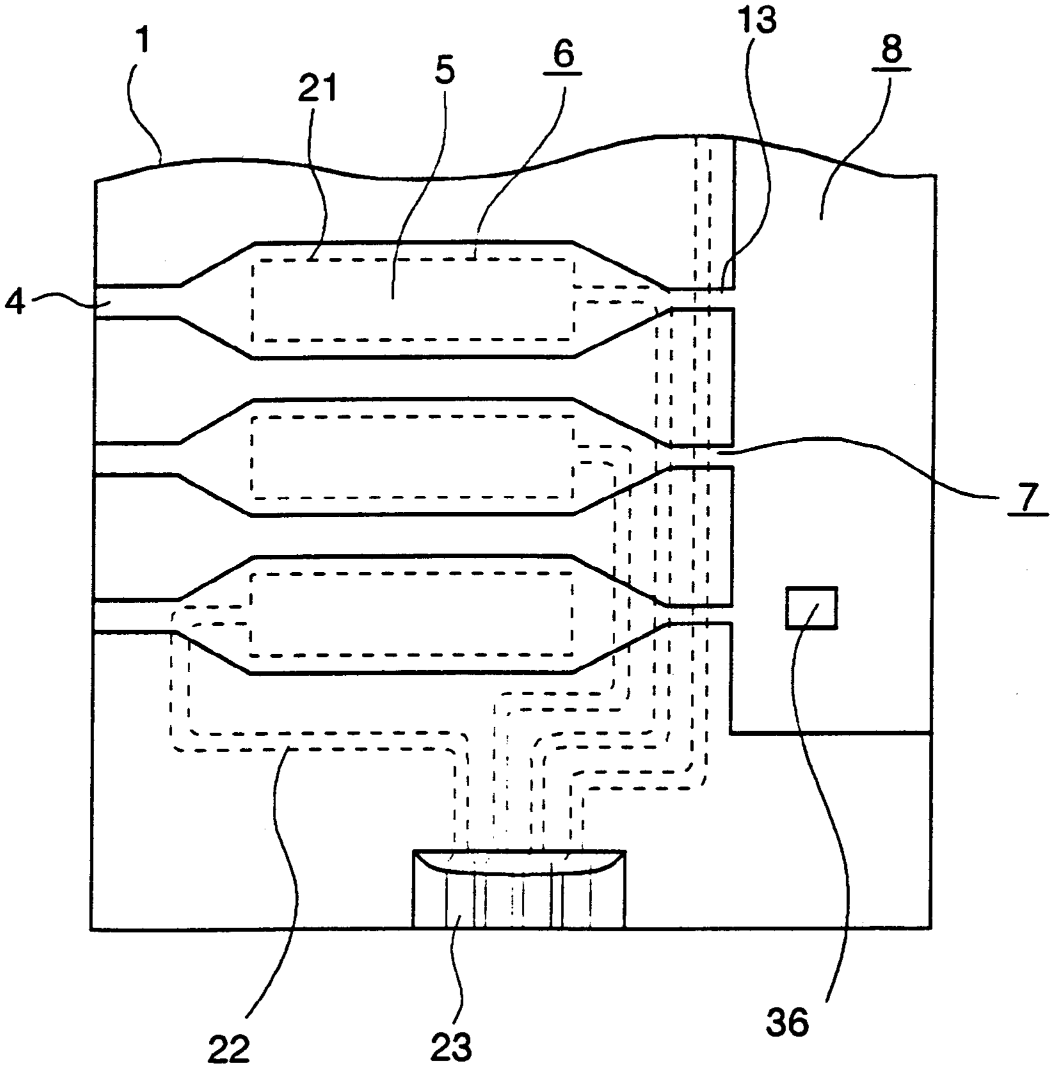

FIG. 5

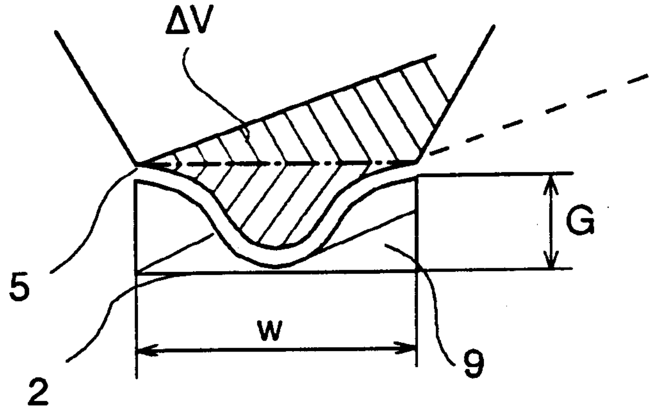

FIG. 6