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(54) **Length-mode drop-on-demand ink jet printhead for ejecting orthogonally directed droplets at improved operating speeds**

(57) A length-mode ink jet printhead which includes an active lower body portion, a series of active intermediate body portions and an inactive upper body portion which collectively define a series of generally parallel channels which extend between front and rear side surfaces of the printhead. Each channel is bounded by first and second sidewalls, each comprised of a lower body projection and an intermediate body portion conductively mounted thereto. Formed in the upper body portion are a series of ink ejection orifices, each of which extends from the top side surface to a corresponding one of the series of channels and is located midway between the front and rear side surfaces of the printhead. Mounted on the front and rear side surfaces of the printhead are acoustic pressure wave reflection interfaces for respectively reflecting forwardly and rearwardly propagating pressure waves generated in the series of channels. An orthogonally directed droplet of ink is ejected from an ink ejection orifice by imparting an acoustic pressure wave to a selected channel in communication with the ink ejection orifice.

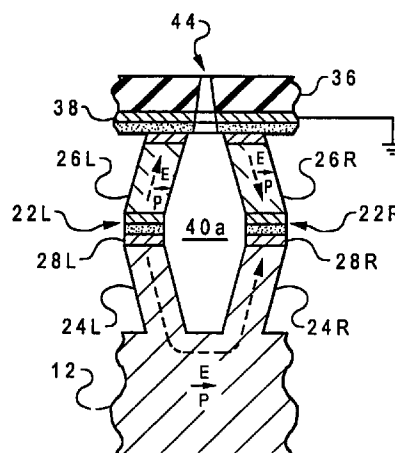


Fig. 5

EP 0 716 926 A2

Description

The present invention generally relates to ink jet printhead apparatus and, more particularly, to a length-mode drop-on-demand ink jet printhead for ejecting orthogonally directed droplets, i.e., droplets ejected in a direction generally orthogonal to the printhead's orifice plane, at improved operating speeds.

Ink jet printing devices use the ejection of tiny droplets of ink to produce an image. As such devices produce highly reproducible and controllable droplets, a droplet may be printed at a location specified by digitally stored image data. One type of ink jet printing device is generally referred to as a "drop-on-demand" type ink jet printing device. In a drop-on-demand ink jet printing device, droplets of ink are ejected from the printhead in response to a specific command related to the image to be produced.

The quality of the image produced by an ink jet printing device is commonly measured by the resolution of the device in dots per inch (or "dpi"). By increasing the resolution of an ink jet printing device, the resultant images produced thereby will more closely resemble full or continuous tone images. To increase the resolution of drop-on-demand ink jet printing devices, considerable efforts have been made to form as many individual channels in as small a space as possible. Thus, "high density" drop-on-demand ink jet printheads, generally characterized by a channel density greater than 125 channels per linear inch, have become increasingly common.

To produce piezoelectrically driven high density ink jet printheads, designers have tended to longitudinally elongate the channels in the direction normal to the substrate on which the image is formed. Quite often, the channels are formed generally parallel with each other along their elongated longitudinal extension and are separated from adjacent channels by sidewalls formed of piezoelectrically deflectable material used to selectively impart pressure pulses into the adjacent channels by application of an electric field thereto. See, for example, U.S. Patent Nos. 3,850,049 to Zoltan, 4,536,097 to Nilsson, 4,879,568 to Bartky et al., 4,887,100 to Michaelis et al., 5,227,813 to Pies et al. and 5,235,352 to Pies et al. Furthermore, in that the longitudinal extension of the channels of such ink jet printheads is large, relative to both the width of the channels and the height of the piezoelectrically deflectable sidewalls separating the channels, e.g., both on the order of a greater than 10:1 ratio, such ink jet printheads may be further classified as "length-mode" ink jet printheads.

For many length-mode ink jet printheads such as those disclosed in the above-referenced patents, the longitudinal extension of the channels are bounded by an ink ejection orifice on one end and by an interconnection with an ink supply on the other. For such length-mode ink jet printheads, this longitudinal extension creates a single dominant acoustic resonance frequency which is proportional to the length of the channels. Furthermore, the length of this longitudinal extension of the channels

acts as limit on the maximum operating frequency of the printhead. More specifically, in order to prevent operating frequency induced variations in the volume and/or velocity of droplets ejected by a channel of a length-mode ink jet printhead, the channel must be limited to operating frequencies below the second or third subharmonic, i.e. $f_{RES}/2$ or $f_{RES}/3$ of the resonant frequency f_{RES} . Thus, if an increase in the operating speed of a length-mode ink jet printhead is desired, the length of the channels may be reduced appropriately.

In order to improve the resolution of the length-mode ink jet printhead, increases in droplet velocity and/or droplet volume are often contemplated. However, if the channel-to-channel pitch of the printhead is to remain constant, these desired increases may only be achieved by increasing the length of the channels. However, by increasing channel length, the acoustic resonant frequency f_{RES} of the channel is decreased, thereby lowering the maximum frequency at which droplets may be ejected and decreasing the speed at which the printhead may be operated. Thus, two very common goals--increased operating speed and increase droplet volume and/or velocity--often conflict with each other.

Another drawback to increasing the channel length in length-mode ink jet printheads is an associated increase in pressure drop within the channels due to viscous losses. More specifically, as droplets of ink are ejected from a channel, capillary pressure induces replenishing ink to flow towards the orifice of the channel to compensate for the losses in ink due to droplet ejection. This capillary pressure is controlled by various factors which include orifice geometry, orifice material, surface tension and the shape and position of the ink meniscus. As the rate at which droplets are ejected from the channel is increased, the rate of ink flow in the channel and the pressure drop within the channel due to viscous losses increase. If droplets are formed at a sufficiently high rate, the viscous losses at the orifice will exceed the rate at which the capillary pressure can replenish the ink. If operation is attempted at such frequencies, the printhead will compensate for such unreplenished losses of ink by decreasing the volume of the droplets ejected at these frequencies. However, as variations in droplet volume are unacceptable, the maximum operating frequency of the printhead must be limited to speeds at which viscous losses will not occur. To achieve a reduction in viscous losses (and a resultant increase in operating speed), the length of the channel may be reduced. As before, however, this solution directly conflicts with the desire to increase droplet volume and/or velocity.

EP-A-0648161 disclosed a page wide ink jet printhead having a series of elongated grooves formed in a block of active piezoelectric material. A corresponding series of channels are then formed by covering the grooves with a sheet of polymer material. Rather than placing the ink ejection orifices at one end of the resultant channels, the open ends of the channels are dammed and ink ejection orifices are ablated in the sheet of pol-

ymmer material which forms the roof of the channels. However, as the orifices are formed proximate to one end of the channels, the resonant frequency of the channels are not significantly affected by placement of the orifices along the roof thereof. Accordingly, the frequency at which a selected channel may be actuated will not vary appreciably due to placement of its ink ejection orifice along the roof of the channel.

It can be readily seen from the foregoing that it would be desirable to provide an improved length-mode drop-on-demand type ink jet printhead drive system characterized by higher operating speeds than that of existing length-mode ink jet printheads of equal length. It is accordingly an object of the present invention to provide such an improved drop-on-demand type ink jet printhead.

In one embodiment, the present invention is of a length-mode ink jet printhead having a main body portion having a channel defined by an interior front wall, an interior rear wall and an interior sidewall longitudinally extending therebetween. An ink ejection orifice in communication with the channel extends between the interior sidewall and an exterior sidewall of the main body portion. Also provided are means for supplying ink to the channel and means for imparting an acoustic pressure wave to ink contained in the channel such that a droplet of ink will be ejected through the orifice. In further aspects thereof, the channel is formed to have a length to height ratio of at least 10:1 and a length to width ratio of at least 10:1.

In further aspects thereof, the interior sidewall is comprised of a first wall at least partially formed of an active piezoelectric material and a second wall formed of an inactive material. In this aspect, means for applying an electric field to the first wall to cause a piezoelectric deflection of the first wall is also provided. In another aspect, the ink ejection orifice is formed in the second wall and extends between the channel and a top side surface included as part of the exterior surface of the main body portion.

In still further aspects thereof, the ink ejection orifice is located midway between the interior front wall and the interior rear wall of the printhead and the means for supplying ink to the channel includes an ink supply, a first ink conduit having a first end coupled to the ink supply and a second end coupled to the channel at the interior front wall, and a second ink conduit having a first end coupled to the ink supply and a second end coupled to the channel at the interior rear wall.

In another embodiment, the present invention is of a length-mode ink jet printhead comprised of a body portion having a series of general parallel channels extending between an exterior front wall and an exterior rear wall of the body portion. Each of the channels are bounded by first and second interior sidewalls at least partially formed of active piezoelectric material. A series of ink ejection orifices are formed in the body portion such that each one extends from an exterior sidewall thereof to a corresponding one of the series of channels.

Also provided are means for supplying ink to the channels and means for imparting an acoustic pressure wave to ink contained in a selected one of the channels to eject a droplet of ink from the ink ejection orifice in communication with the selected channel.

In this embodiment, the length-mode ink jet printhead further includes a first acoustic pressure wave reflection interface coupled to the exterior front wall of the main body portion and a second acoustic pressure wave reflection interface coupled to the exterior rear wall of the main body portion such that forwardly propagating pressure waves generated in the series of channels are reflected off the first acoustic pressure wave reflection interface and rearwardly propagating pressure waves generated in the series of channels are reflected off the second acoustic pressure wave reflection interface. In one aspect thereof, each one of the series of channels has a length to height ratio of greater than 10:1 and, in another aspect thereof, each one of the series of channels has a length to height ratio of between about 25:1 and about 250:1.

In another aspect of this embodiment of the invention, the ink ejection orifices are positioned such that each one communicates with the corresponding one of the channels midway between the first acoustic pressure wave reflection interface and the second acoustic pressure wave reflection interface. In a further aspect thereof, the first acoustic pressure wave reflection interface includes a first manifold plate having a front side surface, a rear side surface coupled to the front side surface of the body portion, a first manifold in communication with each one of the channels and grooved in the rear side surface and a first interior conduit which extends between the first manifold and the front side surface. In still another aspect thereof, the ink supply means is comprised of an ink supply coupled to the first interior conduit at the front side surface of said first manifold plate.

Similarly, in still yet another aspect thereof, the second acoustic pressure wave reflection interface includes a second manifold plate having a front side surface, a rear side surface coupled to the rear side surface of the body portion, a second manifold in communication with each one of the channels and grooved in the rear side surface and a second interior conduit which extends between the second manifold and the front side surface. In still further aspects thereof, the ink supply means includes an ink supply coupled to the first interior conduit at the front side surface of the first manifold plate and to the second interior conduit at the front side surface of the second manifold plate and the means for imparting an acoustic pressure wave to ink contained in a selected one of the series of channels includes means for applying an electric field to the first and second sidewalls bounding the selected channel to cause a piezoelectric deflection thereof.

In yet another aspect of this embodiment of the invention, the body portion of the length-mode ink jet printhead includes a lower body section having an upper side surface and a series of generally parallel spaced

projections extending longitudinally along the upper side surface between the front and rear side surfaces and upwardly therefrom. A bottom side surface of an intermediate body section is conductively mounted to a top side surface of a corresponding one of the lower body projections. A lower side surface of an inactive upper body section in which the ink ejection orifices are formed is conductively mounted to a top side surface of each one of the intermediate sections.

In one aspect thereof, the lower body section is formed of an active piezoelectric material poled in a first direction. In this aspect, the means for applying an electric field to the first and second sidewalls further comprises means for applying an electric field between the bottom side surface of the intermediate body section of the first sidewall and the bottom side surface of the intermediate body section of the second sidewall. In another aspect thereof, each of the intermediate sections are formed of an active piezoelectric material poled in the first direction. In this aspect, the means for applying an electric field to the first and second sidewalls further comprises means for applying a first electric field between the bottom and top side surfaces of the intermediate body section of the first sidewall and a second electric field between the bottom and top side surfaces of the intermediate body section of the second sidewall.

In yet another embodiment, the present invention is of a length-mode ink jet printhead comprised of a lower body portion formed of an active piezoelectric material poled in a first direction, a series of intermediate body portions formed of an active piezoelectric material and poled in the first direction and an upper body portion formed of an inactive material. The lower body portion includes a front side surface, a rear side surface, an upper side surface and a series of generally parallel spaced projections extending longitudinally along the upper side surface between the front and rear side surfaces and upwardly therefrom. Each one of the series of intermediate body portions includes a front wall, a rear wall and a bottom side surface conductively mounted to a top side surface of a corresponding one of the lower body projections. The upper body portion includes a top side surface and a bottom side surface conductively mounted to a top side surface of each one of the intermediate body portions. The lower, intermediate and upper body portions define a series of generally parallel channels which extend between front and rear side surfaces of the lower and intermediate body portions and which are bounded by first and second sidewalls. Thusly, each of the sidewalls bounding a channel are comprised of one of the lower body projections and the intermediate body portion conductively mounted thereto. Formed in the upper body portion are a series of ink ejection orifices, each of which extends from the top side surface to a corresponding one of the series of channels.

The length-mode ink jet printhead further includes first and second manifold plates. A rear side surface of the first manifold plate is coupled to the front side surfaces of the lower, intermediate and upper body portions.

Similarly, a rear side surface of a second manifold plate is coupled to the rear side surfaces of the lower, intermediate and upper body portions. Each manifold plate includes a manifold grooved in the rear side surface and in communication with each one of the channels of the printhead. Each manifold plate provides an acoustic pressure wave reflection interface for respectively reflecting forwardly and rearwardly propagating pressure waves generated in the series of channels.

Ink is supplied to the ink jet printhead by an ink supply coupled to the first interior conduit at the front side surface of the first manifold plate and to the second interior conduit at the front side surface of the second manifold plate. A droplet of ink is ejected from an ink ejection orifice located midway between the rear side surfaces of the first and second manifold plates by means for imparting an acoustic pressure wave to a selected channel in communication with the ink ejection orifice. The means for imparting an acoustic pressure wave includes means for applying a first electric field between the bottom side surface of the intermediate body portion of the first sidewall and the bottom side surface of the intermediate body portion of the second sidewall, means for applying a second electric field between the bottom and top side surfaces of the intermediate body portion of the first sidewall and means for applying a third electric field between the bottom and top side surfaces of the intermediate body portion of the second sidewall. In one aspect thereof, each one of the series of channels has a length to height and length to width ratios of greater than 10:1 and, in another aspect thereof, each one of the series of channels has length to height and length to width ratios of between about 25:1 and about 100:1.

FIG. 1 is a perspective view of a length-mode drop-on-demand ink jet printhead constructed in accordance with the teachings of the present invention; FIG. 2 is a partial cross-sectional view of the ink jet printhead of FIG. 1 taken along lines 2--2 thereof; FIG. 3 is a partially broken away, cross-sectional view of the ink jet printhead of FIGS. 1-2 taken along lines 3--3 of FIG. 2; FIG. 4 is a timing diagram illustrating the voltage waveform applied to a selected piezoelectric sidewall actuator to impart a pressure pulse to a selected channel of the ink jet printhead of FIGS. 1-3; and FIG. 5 is a perspective view of a single channel of the ink jet printhead of FIGS. 1-3 being actuated to eject a droplet of ink therefrom.

Referring now to the drawings wherein thicknesses and other dimensions have been exaggerated in the various figures as deemed necessary for explanatory purposes and wherein like reference numerals designate the same or similar elements throughout the several views, in FIGS. 1-2, an length-mode drop-on-demand ink jet printhead 10 constructed in accordance with the teachings of the present invention will now be described in greater detail. By the term "length-mode", it is intended

to refer to an ink jet printhead dimensioned such that the ratio of the length of the channel to the height of the side walls is greater than 10:1 and the ratio of the length of the channel to the width of the channel is also greater than 10:1. It should be noted, however, that while an ink jet printhead having a channel length to sidewall height ratio greater than 10:1 and a channel length to channel width ratio greater than 10:1 may be considered a length-mode ink jet printhead, length-mode ink jet printheads are typically dimensioned to have a channel length to sidewall height ratio of between about 25:1 and about 250:1. For example, it is contemplated that the length-mode ink jet printhead 10 may be dimensioned to have a channel length of 15 mm, a sidewall height of 100 μm , a channel width of 90 μm and a sidewall width of 80 μm .

The ink jet printhead 10 is comprised of first and second body parts 12, 14, having respective top and bottom surfaces 12a, 12b and 14a, 14b. Preferably, the first and second body parts 12, 14 are similarly sized along their respective length and width dimensions. Relative to the height dimension, however, the second body part 14 is shorter than the first body part 12. Preferably, both the first and second body parts 12, 14 are formed of a piezoelectric material, for example, PZT, poled in direction P although, in an alternate embodiment of the invention, the first body part 12 may be formed of an inactive material. Layers 16, 18, 20 of conductive material are formed along the top side surface 12a of the first body part 12, the bottom side surface 14b of the second body part 14 and the top side surface 14a of the second body part 14, respectively, for example, using a conventional metal deposition process. The first and second body parts 12, 14 are aligned along respective front surfaces 12c, 14c and the layers 16, 18 are conductively bonded to each other using a layer of conductive adhesive (not shown in FIG. 1).

After conductively bonding the first and second body parts 12, 14 together, a series of generally parallel grooves which downwardly extend through the conductive layer 20, the second body part 14, the conductive layer 18, the layer of conductive adhesive, the conductive layer 16 and a portion of the first body part 12, and which longitudinally extend from the front side surfaces 14c, 12c to back side surfaces 14d, 12d, are formed, preferably using a machining or other sawing process. By forming the grooves, a series of piezoelectric sidewall actuators 22, each comprised of a first sidewall part 24 and a second sidewall part 26, are produced.

The first sidewall part 24 includes a strip 28 of conductive material formed from the conductive layer 16 during the grooving process and is integrally formed with the first body part 12 on one side thereof. The second sidewall part 24 includes lower and upper strips 30 and 32 of conductive material located on opposite sides thereof and respectively formed from the conductive layers 18 and 20 during the grooving process. The strips 28 and 30 are conductively mounted to each other by a strip 34 of conductive adhesive formed from the layer of conductive adhesive, again during the grooving process.

An orifice plate 36 having a layer 38 of conductive material formed on a lower side surface 36b thereof is conductively mounted to the strips 32 to form a series of ink-carrying channels 40 from the grooves. More specifically, a layer 42 of conductive adhesive is applied to the layer 38 of conductive material, front and rear side surface 36c, 36d of the orifice plate 36 are aligned with the front and rear side surface 14c, 14d of the second body part 14 and the orifice plate 36 and the second body part 14 mated.

Turning momentarily to FIG. 3, a series of ink ejection orifices 44, each of which corresponds to one of the channels 40, are formed in the orifice plate 36. Each orifice 44 extends from a first opening 44b located along the bottom side surface 36b of the orifice plate 36 to a second, narrower, opening 44a located along a top side surface 36a of the orifice plate 36. The orifices 44 are located along a line generally parallel to, and midway between, the front and rear side surfaces 36c, 36d of the orifice plate 36. By mounting the orifice plate 36 to the second body part 14, the opening 44b of each orifice 44 is placed in communication with a corresponding one of the channels 40 at the general center of the longitudinal extension of the channel 40, i.e. midway between front and rear side openings 40c, 40d of the channel 40. It is contemplated that a laser ablation process may be used to form the orifices 44 in the orifice plate 36. Preferably, the orifices 44 are formed after the orifice plate is mounted onto the second body part 14, for example, in accordance with the method set forth in U.S. Patent No. 5,208,980 to Hayes.

Returning now to FIG. 1, the ink jet printhead 10 is coupled to an ink supply system which includes an ink supply 46, a front manifold plate 48 and a rear manifold plate 50. Each of the channels 40 is filled with ink received from the ink supply system connected with the front and rear openings 40c, 40d of each of the channels 40. In a manner subsequently described, each horizontally opposed pair of the piezoelectric sidewall actuators 22 is piezoelectrically deflectable into and out of their associated channel 40 to force ink (in droplet form) outwardly through the orifice 44 associated with the actuated channel 40.

Each manifold plate 48, 50 includes an interior side surface 52, 56 and a manifold 54, 58 formed along the interior side surface 52, 56. The interior side surface 52 of the front manifold plate 48 is mounted to the front side surfaces 12c, 14c of the first and second body parts 12, 14 such that the manifold 54 is in communication with the front opening 40c of each one of the channels 44. Similarly, the interior side surface 56 of the rear manifold plate 50 is mounted to the rear side surfaces 12d, 14d of the first and second body parts 12, 14 such that the manifold 58 is in communication with the rear opening 40d of each one of the channels 44. Each manifold plate 48, 50 further includes an internal conduit 60 which extends between the exterior side surfaces 64, 66 and the manifolds 54, 58. The ink supply system further includes an external conduit 68 connected to the internal

conduit 60 of the front manifold plate 48 and the internal conduit (not visible) of the rear manifold plate 50.

As will be more fully described below, the front and rear manifold plates 48, 50 provide first and second acoustic pressure wave reflection interfaces for the channels 40. It is contemplated that the front and rear manifold plates 48, 50 may provide the desired acoustic pressure wave reflection interfaces by either providing a large change in cross-sectional area in the transition between the channels 40 and the front and rear manifolds 54 and 58, or by being formed of a material having a much greater compliance than the material forming the walls of the channels 40, or by both. This type of acoustic pressure wave reflection interface would have a reflection coefficient approaching -1.0 so that the resonance behavior is similar to the resonance behavior of an open organ pipe.

To electrically connect the ink jet printhead 10, the layer of conductive material 38 should be electrically connected to ground, as schematically illustrated in FIG. 2, and each one of the conductive strips 28 is electrically connected to a driver capable of selectively applying a positive or negative voltage thereto. For example, each conductive strip 28 may be electrically connected to a conductive pin 72 which extends through the first body part 12 and projects from the bottom side surface 12b thereof. A driver board 70 having a plurality of pin-receiving apertures (not shown) for receiving the portions of the pins 72 projecting from the lower side surface 12b may be snap-mounted onto the bottom side surface 12b of the first body part 12. Preferably, the driver board 70 should include a controller for issuing control signals to actuate selected ones of the piezoelectric sidewall actuators 22 and a series of switching structures capable of generating a positive or negative voltage at an output thereof in response to instructions issued by the controller. When the driver board 46 is snap-mounted onto the lower body part 12, each output of a switching structure should become electrically connected with one of the pins 72. Thus, a snap-in driver board 70 may be used to provide a separate electrical connection to every conductive strip 28. As will be more fully described below, by applying a selected voltage to selected conductive strips 28, the piezoelectric sidewall actuators 22 in which the conductive strips 28 are embedded may be deflected relative to the channels 40 bounded by the selected piezoelectric sidewall actuator 22 to impart a pressure pulse thereto which effects the ejection of a droplet of ink therefrom. Of course, the portion of the pins 72 extending through the first body part 12 should be electrically isolated therefrom, for example, using a layer of insulative material (not shown), to prevent the pins 72 from shorting the electric fields which causes selected piezoelectric sidewall actuators 22 to deflect. Further details regarding the electrical interconnection of the printhead 12 and the driver board 70, as well as switching structures suitable for applying selected voltages to the conductive strips 28 are set forth in co-pending U.S. Patent Application Serial Nos. 08/060,297 and 08/060,298, both filed May 10,

1993, and 08/066,396, filed May 20, 1993, all of which are hereby incorporated by reference as if reproduced in their entirety.

In an alternate embodiment of the invention not shown in the drawings, the driver board 70 may be omitted and the conductive strips 28 interconnected with a controller (not shown) by means of conductive electrical leads (also not shown) which extend through either of the front manifold plate 48 or the rear manifold plate 50. As the front and rear manifold plates 48 and 50 are formed of an inactive material, in this embodiment of the invention, any such conductive electrical leads which extend through the manifold plates 48, 50 do not need to be insulated.

Referring next to FIG. 4, a voltage waveform 74, also referred to as an echo pulse waveform, which includes primary and echo portions 74a, 74b for generating a pressure wave in a selected channel 40 of the ink jet printhead 10 to cause the ejection of an orthogonally directed droplet of ink therefrom will now be described in greater detail. From a rest state 76, during which a rest state voltage is applied to the conductive strip 28 and the piezoelectric sidewall actuator 22 remains in a undeflected rest position, the voltage waveform 74 begins a rapid rise 78 at time T_1 in the voltage applied to the conductive strip 28. The voltage rise 78 causes the piezoelectric sidewall actuator 22 to begin to move towards a first, outwardly deflected position, thereby producing an expansive acoustic pressure wave in the channel 40 partially defined thereby.

The resonant frequency f_{RES} for the channels 40 of the ink jet printhead 10 is equal to the wavespeed of the acoustic pressure waves generated in the channels 40 divided by the length of the channels 40. For the channels 40, the length of the channels 40 is determined from the distance from the orifice 44 to the acoustic pressure wave reflection interfaces provided by the front and rear manifolds 48 and 50. Thus, as illustrated in FIG. 3, the resonant frequency f_{RES} for the channels 40 is $L/2$ where L is the length of the channels 40. This results from the fact that the orifice 44 creates a fixed pressure boundary condition where the reflection coefficient approaches -1.0. In other words, the pressure waves will not propagate across the orifice 44 from one side to the other.

The acoustic wave generated by the deflection of the piezoelectric sidewall actuator 22 is a longitudinal wave having a fluid velocity directed parallel to the direction of propagation. When such an acoustic wave reaches the orifice 44, it encounters a fixed atmospheric pressure boundary condition which forces the acoustic wave to redistribute the energy from potential energy, i.e., a pressure gradient K (see FIG. 3) within the channel 40, to kinetic energy, i.e., the velocity of an orthogonally directed droplet ejected from the orifice 44 or other movement of the ink meniscus at the orifice 44. As the direction of the fluid velocity produced during the conversion process is determined by the pressure gradient, and as the pressure gradient is orthogonal to the orientation of the orifice 44, the direction of the kinetic energy pro-

duced during the conversion process is determined by orientation of the orifice 44, which, in the embodiment of the invention disclosed herein, is perpendicular to the longitudinal extension of the channel 40. Accordingly, droplets ejected from the orifice 44 will travel in a direction generally orthogonal to the orifice plate 36 and the channel 40.

It should be further noted that, in that the generated acoustic pressure waves cannot propagate past the pressure gradient and must be converted into kinetic energy at the orifice 44, the orifice 44 effectively divides the channel 40 into a first (or forward) part and a second (or rearward) part. Both the forward and rearward part of the channel 40 has a discrete resonant frequency proportional to the length of that part of the channel. However, if the orifice 44 is located at the midpoint of the channel 40, this resonant frequency is the same for both parts of the channel 40 and is one-half the resonant frequency for a length-mode channel having an orifice at one end thereof.

The expansive acoustic pressure wave produced by the outward deflection of the piezoelectric sidewall actuator 22 begins to propagate both forwardly and rearwardly through both the forward and rearward parts of a channel 40 partially defined thereby. The rearwardly propagating portion produced in the forward part of the channel 40 and the forwardly propagating portion produced in the rearward part of the channel 40 will encounter the pressure gradient at the orifice 44 and be converted into kinetic energy. However, as the extent of the outward deflection of the piezoelectric sidewall actuator 22 is controlled such that, absent reinforcement thereof, a pressure wave produced thereby lacks sufficient energy to overcome the surface tension of the meniscus of the ink located at the orifice 44, the meniscus will fluctuate somewhat but no droplets of ink will separate from the ink contained in the channel 40.

Once reaching a first or peak value at time T_2 , the voltage waveform 74 enters a primary dwell state 80 which extends from time T_2 to time T_3 . During the primary dwell state 80, the voltage is held constant at the first value to hold the piezoelectric sidewall actuator 22 in the deflected position. While the voltage waveform 74 is held in the dwell state 80, the forwardly propagating pressure wave in the forward part of the channel 40 and the rearwardly propagating pressure wave in the rearward part of the channel 40 will have reflected off the interfaces with the ink supply 46 located at the front and rear openings 40c, 40d of the channel 40 and returned to their origination point. When the reflected pressure waves reach their origination point at time T_3 , the voltage waveform 74 begins a rapid fall 82 during which the voltage drops below the rest voltage (thereby ending the primary portion 74a and beginning the echo portion 74b of the echo pulse 74) to a second, lower value at time T_4 . During the fall 82, the voltage applied to the conductive strip 28 drops to the second value, thereby causing the piezoelectric sidewall actuator 22 to move, from the first, outwardly deflected position, past the rest position, and into

a second, inwardly deflected position which compresses the channel 40. By compressing the channel 40, the piezoelectric sidewall actuator 22 imparts a second pressure wave into the channel 40 which reinforces the rearwardly propagating reflected pressure wave in the forward part of the channel 40 and the forwardly propagating reflected pressure wave in the rearward part of the channel 40.

Once reaching the second, lower value, the voltage waveform 74 enters an echo dwell state 84 which extends from time T_4 to time T_5 . During this state, the voltage is held constant at the second value to hold the piezoelectric sidewall actuator 22 in the second, channel compressing, deflected position. While the voltage waveform 74 is held in the echo dwell state 84, the reinforced pressure waves will propagate towards the orifice 44 where the pressure waves now have sufficient strength to overcome the surface tension of the meniscus of the ink when converted into kinetic energy. At time T_5 , the voltage waveform 74 will begin a second rise 86 which will return the voltage waveform 74 to the rest state 76 at time T_6 . The piezoelectric sidewall actuator 22 will move from the second, channel compressing, deflected position to the rest position, thereby imparting a negative pressure wave into the channel 40. This negative pressure wave acts as an active pull-up which prematurely terminates the droplet formation process by the rearwardly propagating reinforced pressure wave in the forward part of the channel 40 and the forwardly propagating reinforced pressure wave in the rearward part of the channel 40. Having returned to the rest state, the voltage waveform 74 remains at this state to allow the pressure pulse within the channel 40 to dissipate over time.

In an exemplary embodiment of the invention, the rest, first and second voltages may be 0, +20 and -20 volts, respectively, the rise, fall, and return times may all be 5 μ sec, the dwell time may be 15 μ sec and the echo dwell time may be 30 μ sec. It is further contemplated that the rise, fall and return times may be effectively reduced to zero if a suitably configured digital switching system such as that disclosed in co-pending U.S. Patent Application Serial Nos. 08/060,297 or 08/060,298 is incorporated as part of the drive system for the ink jet printhead 10.

Referring next to FIG. 5, an illustrative actuation of a channel 40a to drive a quantity of ink therein, in droplet form, outwardly through the associated ink discharge orifice 44 will now be described in greater detail. Prior to the actuation of the channel 40a, its horizontally opposed left and right sidewall actuators 22_L and 22_R are (at time T_0 in FIG. 5) in initial, laterally undeflected (or "rest") positions such as that illustrated in FIG. 2. To eject a droplet of ink from the channel 40a, the voltage waveform 74 is applied to the conductive strip 28_L separating the lower and upper sidewall parts 24_L , 26_L of the piezoelectric sidewall actuator 22_L while a second voltage waveform of opposite polarity, relative to the rest state voltage 76, to the voltage waveform 74 is simultaneously applied to

the conductive strip 28_R separating the lower and upper sidewall parts 24_R, 26_R of the piezoelectric sidewall actuator 22_R to initiate the channel actuation cycle. Accordingly, at time T₁, the left conductive strip 28_L would have the voltage rise 78 imposed thereon during the time interval T₁ - T₂, reaching the primary dwell state 80 where a constant positive voltage is applied thereto, at time T₂. Simultaneously, at time T₁, the right conductive strip 28_R would have an equal negative voltage drop imposed thereon during the time interval T₁ - T₂, reaching a negative dwell state where a constant negative voltage (relative to the rest voltage) is applied thereto at time T₂.

These opposite polarity voltage pulses, would produce a first voltage drop (+20 volt to 0 volt) between the conductive strip 28_L and the conductive layer 38, a second voltage drop (0 volt to -20 volt) between the conductive layer 38 and the conductive strip 28_R and a third voltage drop (+20 volt to -20 volt) between the conductive strip 28_L and the conductive strip 28_R. As the first, second and third electric fields produced by the first, second and third voltage drops are generally orthogonal to the poling direction of the sidewall parts 26_L, 28_L, 26_R, 28_R, the piezoelectric sidewall actuators 22_L and 22_R are outwardly deflected away from the channel 40a being actuated and into the outwardly adjacent channels (not shown), thereby imparting respective compressive pressure pulses to the outwardly adjacent channels and expansive pressure pulses to the channel 40a which propagate forwardly and rearwardly in both the forward and rearward parts of the channel 40. As the sidewall actuators 22_L and 22_R are held in the outwardly deflected position, the rearwardly propagating portion of the acoustic pressure wave imparted to the rearward part of the channel 40a reflects off the rear manifold plate 50 of the ink jet printhead 10 and begins to propagate forwardly in the channel 40a while the forwardly propagating portion of the acoustic pressure wave imparted to the forward part of the channel 40a reflects off the front manifold plate 48 and begins to propagate rearwardly in the channel 40b. The forwardly propagating portion of the acoustic pressure wave imparted to the rearward part of the channel 40a and the rearwardly propagating portion of the acoustic pressure wave imparted to the forward part of the channel 40a are dissipated at the orifice 44.

Next, at time T₃, the positive voltage pulse 70 transmitted to the conductive strip 28_L and the corresponding negative, relative to the rest state voltage 54, voltage pulse on the conductive strip 28_R are terminated and the conductive strip 28_L has the voltage fall 60 imposed thereon during the time interval T₃ - T₄, reaching the echo dwell state 62 where a constant negative, relative to the rest state voltage 54, voltage is applied thereto, at time T₄. Simultaneously, at time T₃, the conductive strip 28_R would have an equal positive voltage rise imposed thereon during the time interval T₃ - T₄, reaching a positive echo dwell state where a constant positive voltage is applied thereto at time T₄. These opposite voltage pulses inwardly deflect the sidewall parts 24_L, 26_L of the piezoelectric sidewall actuator 22_L and the sidewall parts 24_R,

26_R of the piezoelectric sidewall actuator 22_R past their initial undeflected positions and into the channel 40a, thereby simultaneously imparting respective compressive pressure pulses into the channel 40a which reinforces the forwardly propagating reflection of the pressure wave imparted to the rearward part of the channel 40a and the rearwardly propagating reflection of the pressure wave imparted to the forward part of the channel 40a by the outward deflection of the sidewall actuators 22_L and 22_R. Such inward deflection of the actuators 22_L and 22_R elevates the potential energy stored as ink pressure within the channel 40a to an extent sufficient to initiate droplet formation due to the kinetic energy produced when the reinforced acoustic pressure waves arrive at the orifice 44.

Next, at time T₅, the negative, relative to rest state voltage 76, voltage pulse 74 applied to the conductive strip 28_L and the corresponding positive voltage pulse applied to the conductive strip 28_R are terminated and the piezoelectric sidewall actuator 22_L has the second voltage rise 64 imposed thereon during the time interval T₅ - T₆, returning to the rest state 76 at time T₆. Simultaneously, at time T₅, the piezoelectric sidewall actuator 22_R would have an equal negative, relative to the rest state voltage 76, voltage fall imposed thereon during the time interval T₅ - T₆, returning to the rest state at time T₆. By removing the electric fields applied across the sidewall parts 26_L, 28_L, 26_R, 28_R, the piezoelectric sidewall actuators 22_L and 22_R are outwardly deflected back to their respective rest positions. The outward deflection back to the rest position cancels out forwardly propagating pressure waves within the rearward part of the actuated channel 40a and rearwardly propagating pressure waves within the forward part of the actuated channel 40a, thereby causing the premature termination of the formation of the ink droplet within the actuated channel 40a such that the volume of the droplet to be ejected therefrom is determined by the time at which the sidewall actuators 22_L and 22_R are driven back to the rest position. The sidewall actuators 22_L and 22_R are then held at the rest state voltage 76 until any remaining pressure waves within the actuated channel 40a subside over time.

Heretofore, it had been erroneously believed propagation of the pressure wave along the longitudinal extension of the channel effected the ejection of a droplet of ink from the channel. Accordingly, length-mode ink jet printheads uniformly disclosed the ink ejection orifice at one end of the channel. By discovering that it is the pressure condition which occurs at the orifice which causes the ejection of ink in a direction generally orthogonal to the plane of the orifice, considerable flexibility is now possible in future designs of length-mode ink jet printheads. Specifically, the orifice may now be located anywhere along the channel and in any orientation.

Furthermore, by damming the previously open front end of the channels such that acoustic wave reflection interfaces are provided at both the front and rear ends of the channel, an additional boundary for acoustic wave

reflections is created such that, if the orifices of a length-mode ink jet printhead having dammed front and rear ends are placed midway between the front and rear ends of the channels, a clearly superior length-mode ink jet printhead which enjoys a maximum operating frequency twice that of a traditionally designed printhead will result. Specifically, the resonant frequency of a length-mode ink jet printhead in which both the front and rear ends are dammed and the orifices are positioned midway between the front and rear ends is one-half the resonant frequency of a traditionally designed length-mode ink jet printhead having an open front end.

Finally, by coupling the ink supply to both ends of the channel, the distance that a fluid particle must travel within the channel is again half that of traditional designs, thereby cutting viscous flow losses in half and again increasing the maximum operating frequency of the ink jet printhead.

The foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the present invention being limited solely by the appended claims.

Claims

1. A length-mode ink jet printhead, comprising:
 - a body portion having exterior and interior front walls, exterior and interior rear walls and longitudinally extending exterior and interior sidewalls, said interior sidewall extending between said interior front wall and said interior rear wall to define a channel;
 - said body portion having an ink ejection orifice which extends between said interior sidewall and said exterior sidewall;
 - means for supplying ink to said channel; and
 - means for imparting an acoustic pressure wave to ink contained in said channel, said acoustic pressure wave causing ejection of a droplet of ink through said orifice.
2. An length-mode ink jet printhead according to claim 1 wherein said channel has a length to height ratio of greater than 10:1.
3. A length-mode ink jet printhead according to claim 2 wherein said channel has a length to width ratio of greater than 10:1.
4. A length-mode ink jet printhead according to claim 2 wherein said interior sidewall is comprised of a first wall at least partially formed of an active piezoelectric material and a second wall formed of an inactive material.
5. A length-mode ink jet printhead according to claim 4 wherein said means for imparting an acoustic pressure wave to ink contained in said channel further comprises means for applying an electric field

to said first wall to cause a piezoelectric deflection of said first wall.

6. A length-mode ink jet printhead according to claim 5 wherein said exterior surface of said body portion further comprises a top side surface and wherein said ink ejection orifice is formed in said second wall and extends between said channel and said top side surface.
7. A length-mode ink jet printhead according to claim 6 wherein said ink ejection orifice is formed midway between said interior front wall and said interior rear wall.
8. A length-mode ink jet printhead according to claim 7 wherein said means for supplying ink to said channel further comprises:
 - an ink supply;
 - a first ink conduit having a first end coupled to said ink supply and a second end coupled to said channel at said interior front wall; and
 - a second ink conduit having a first end coupled to said ink supply and a second end coupled to said channel at said interior rear wall.
9. A length-mode ink jet printhead, comprising:
 - a body portion having an exterior sidewall, an exterior front wall, an exterior rear wall and a series of generally parallel channels extending between said exterior front wall and said exterior rear wall, each of said channels bounded by first and second interior sidewalls, each of said first and second interior sidewalls being at least partially formed of an active piezoelectric material;
 - said body portion having a series of ink ejection orifices formed therein, each one of said series of ink ejection orifices extending from said exterior sidewall to a corresponding one of said series of channels;
 - means for supplying ink to said series of channels;
 - means for imparting an acoustic pressure wave to ink contained in a selected one of said series of channels to eject a droplet of ink from said ink ejection orifice in communication with said selected channel;
 - a first acoustic pressure wave reflection interface coupled to said exterior front wall of said main body portion, said first acoustic pressure wave reflection interface reflecting forwardly propagating pressure waves generated in said series of channels; and
 - a second acoustic pressure wave reflection interface coupled to said exterior rear wall of said main body portion, said second acoustic pressure wave reflection interface reflecting rearwardly propagating pressure waves generated in said series of channels.

10. A length-mode ink jet printhead according to claim 9 wherein each one of said series of channels has a length to height ratio of greater than 10:1.
11. A length-mode ink jet printhead according to claim 9 wherein each one of said series of channels has a length to height ratio of between about 25:1 and about 250:1. 5
12. A length-mode ink jet printhead according to claim 11 wherein each one of said ink ejection orifices communicates with said corresponding one of said channels midway between said first acoustic pressure wave reflection interface and said second acoustic pressure wave reflection interface. 10 15
13. A length-mode ink jet printhead according to claim 12 wherein said first acoustic pressure wave reflection interface further comprises a first manifold plate having a front side surface, a rear side surface coupled to said front side surface of said body portion, a first manifold in communication with each one of said channels and grooved in said rear side surface and a first interior conduit which extends between said first manifold and said front side surface. 20 25
14. A length-mode ink jet printhead according to claim 13 wherein said ink supply means further comprises an ink supply coupled to said first interior conduit at said front side surface of said first manifold plate. 30
15. A length-mode ink jet printhead according to claim 13 wherein said second acoustic pressure wave reflection interface further comprises a second manifold plate having a front side surface, a rear side surface coupled to said rear side surface of said body portion, a second manifold in communication with each one of said channels and grooved in said rear side surface and a second interior conduit which extends between said second manifold and said front side surface. 35 40
16. A length-mode ink jet printhead according to claim 15 wherein said ink supply means further comprises an ink supply coupled to said first interior conduit at said front side surface of said first manifold plate and to said second interior conduit at said front side surface of said second manifold plate. 45
17. A length-mode ink jet printhead according to claim 16 wherein said means for imparting an acoustic pressure wave to ink contained in a selected one of said series of channels further comprises means for applying an electric field to said first and second sidewalls bounding said selected channel to cause piezoelectric deflection of said first and second sidewalls. 50 55
18. A length-mode ink jet printhead according to claim 16 wherein said body portion further comprises:
a lower body section having an upper side surface and a series of generally parallel spaced projections extending longitudinally along said upper side surface between said front and rear side surfaces and upwardly therefrom, each of said lower body projections having a top side surface;
a series of intermediate body sections, each one of said series of intermediate body sections having a bottom side surface conductively mounted to said top side surface of a corresponding one of said lower body projections; and
an upper body section in which said ink ejection orifices are formed, said upper body section formed of an inactive material and having a lower side surface conductively mounted to a top side surface of each one of said series of intermediate sections.
19. A length-mode ink jet printhead according to claim 18 wherein said lower body section is formed of an active piezoelectric material poled in a first direction and wherein said means for applying an electric field to said first and second sidewalls bounding said selected channel to cause piezoelectric deflection of said first and second sidewalls further comprises means for applying an electric field between said bottom side surface of said intermediate body section of said first sidewall and said bottom side surface of said intermediate body section of said second sidewall.
20. A length-mode ink jet printhead according to claim 18 wherein each of said intermediate sections are formed of an active piezoelectric material poled in a first direction and wherein said means for applying an electric field to said first and second sidewalls bounding said selected channel to cause piezoelectric deflection of said first and second sidewalls further comprises means for applying a first electric field between said bottom and top side surfaces of said intermediate body section of said first sidewall and a second electric field between said bottom and top side surfaces of said intermediate body section of said second sidewall.
21. A length-mode ink jet printhead according to claim 18 wherein said lower body section is formed of an active piezoelectric material poled in a first direction, each of said intermediate sections are formed of an active piezoelectric material poled in said first direction and wherein said means for applying an electric field to said first and second sidewalls bounding said selected channel to cause piezoelectric deflection of said first and second sidewalls further comprises means for applying a first electric field between said bottom side surface of said intermediate body section of said first sidewall and said bottom side sur-

face of said intermediate body section of said second sidewall, a second electric field between said bottom and top side surfaces of said intermediate body section of said first sidewall and a third electric field between said bottom and top side surfaces of said intermediate body section of said second sidewall.

22. A length-mode ink jet printhead, comprising:

a lower body portion formed of an active piezoelectric material poled in a first direction, said lower body portion having a front side surface, a rear side surface, an upper side surface and a series of generally parallel spaced projections extending longitudinally along said upper side surface between said front and rear side surfaces and upwardly therefrom, each of said lower body projections having first and second side surfaces and a top side surface;

a series of intermediate body portions formed of an active piezoelectric material poled in said first direction, each one of said series of intermediate body portions having a front wall, a rear wall, first and second side surfaces, a top side surface and a bottom side surface, said bottom side surface conductively mounted to said top side surface of a corresponding one of said lower body projections;

an upper body portion formed of an inactive material, said upper body portion having a top side surface, a bottom side surface conductively mounted to said top side surface of each one of said intermediate body portions and a series of ink ejection orifices;

said upper side surface of said lower body portion, said first and second side surfaces of said lower body projections, said first and second side surfaces of said intermediate body portions and said bottom side surface of said upper body portion defining a series of generally parallel channels which extend between said front and rear side surfaces of said lower and intermediate body portions;

each one of said channels being bounded by first and second sidewalls, each said sidewall comprised of one of said lower body projections and said intermediate body portion conductively mounted to said lower body projection;

each one of said series of ink ejection orifices extending from said top side surface to a corresponding one of said series of channels;

a first manifold plate having a front side surface, a rear side surface coupled to said front side surfaces of said lower body portion, said intermediate body portions and said upper body portion, a first manifold in communication with each one of said channels and grooved in said rear side surface and a first interior conduit which extends between said first manifold and said front side surface, said first manifold plate providing a first acoustic pressure wave reflection interface for reflecting forwardly propagating pressure waves generated in said

series of channels;

a second manifold plate having a front side surface, a rear side surface coupled to said rear side surfaces of said lower body portion, said series of intermediate body portion and said upper body portion, a second manifold in communication with each one of said channels and grooved in said rear side surface and a second interior conduit which extends between said second manifold and said front side surface, said second manifold plate providing a second acoustic pressure wave reflection interface for reflecting rearwardly propagating pressure waves generated in said series of channels;

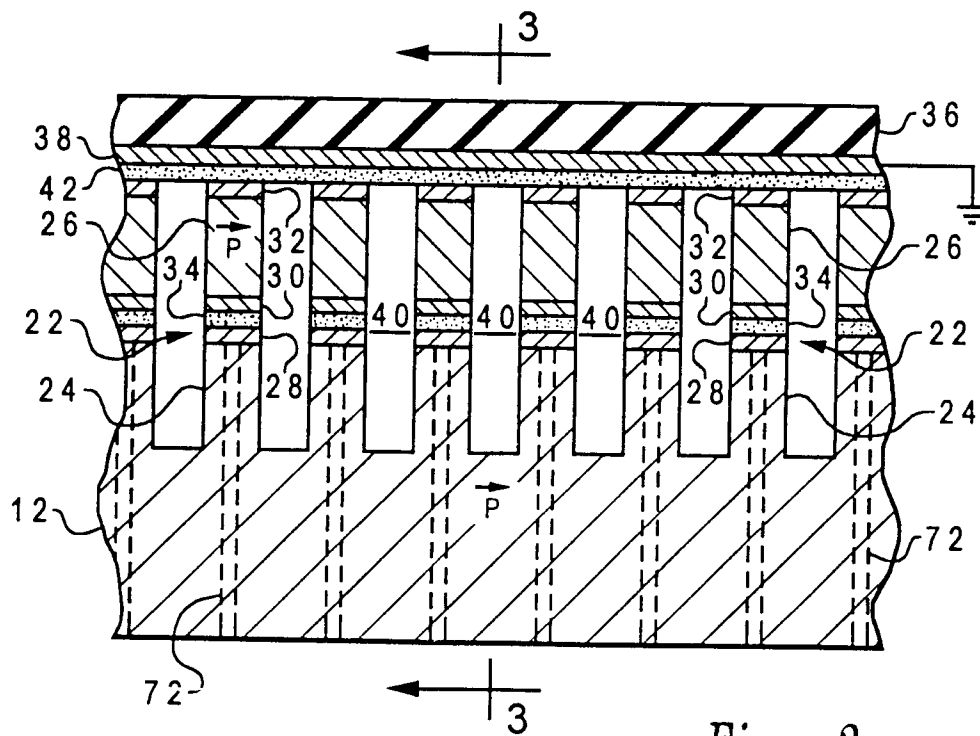
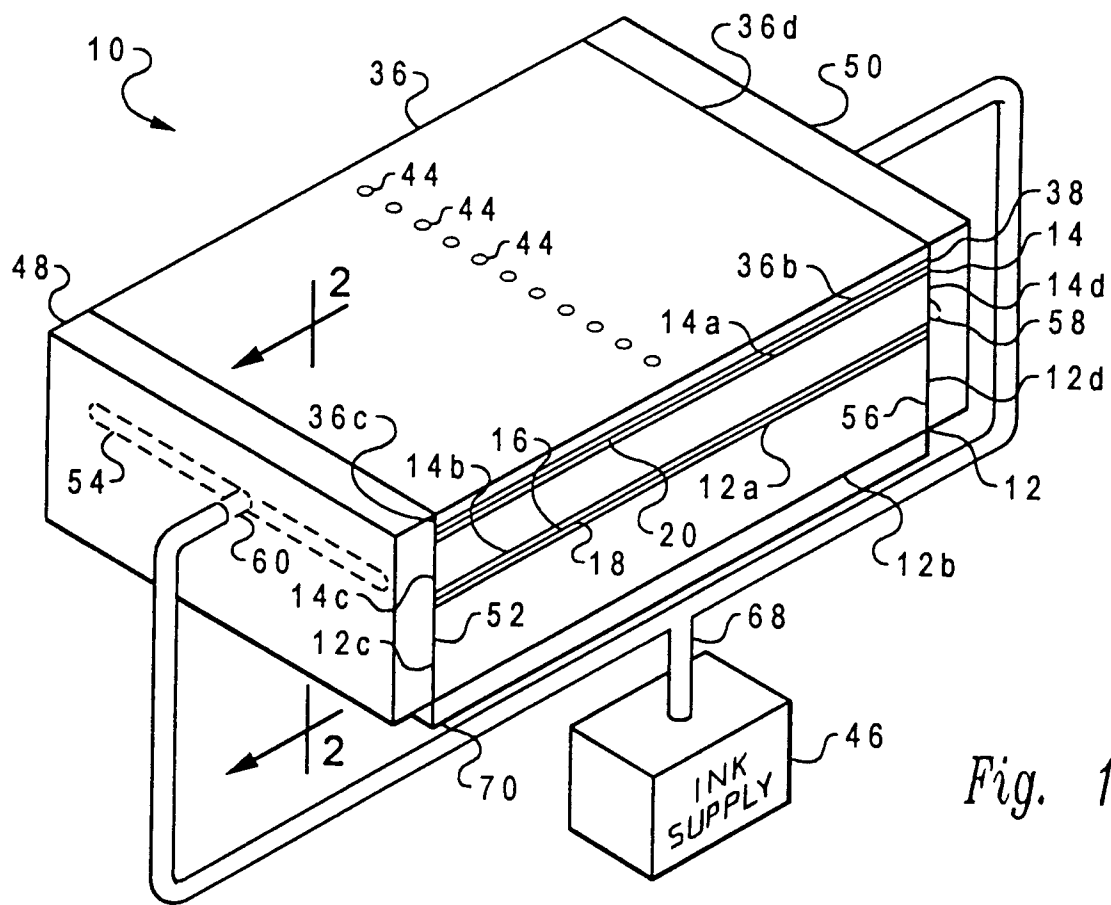
each one of said ink ejection orifices communicating with said corresponding one of said channels midway between said rear side surface of said first manifold plate and said rear side surface of said second manifold plate;

an ink supply coupled to said first interior conduit at said front side surface of said first manifold plate and to said second interior conduit at said front side surface of said second manifold plate;

means for imparting an acoustic pressure wave to ink contained in a selected one of said series of channels to eject a droplet of ink from said ink ejection orifice in communication with said selected channel, said imparting means comprising means for applying a first electric field between said bottom side surface of said intermediate body portion of said first sidewall and said bottom side surface of said intermediate body portion of said second sidewall, means for applying a second electric field between said bottom and top side surfaces of said intermediate body portion of said first sidewall and means for applying a third electric field between said bottom and top side surfaces of said intermediate body portion of said second sidewall.

23. A length-mode ink jet printhead according to claim 22 wherein each one of said series of channels has a length to height ratio of greater than 10:1.

24. A length-mode ink jet printhead according to claim 22 wherein each one of said series of channels has a length to height ratio of between about 25:1 and about 250:1.



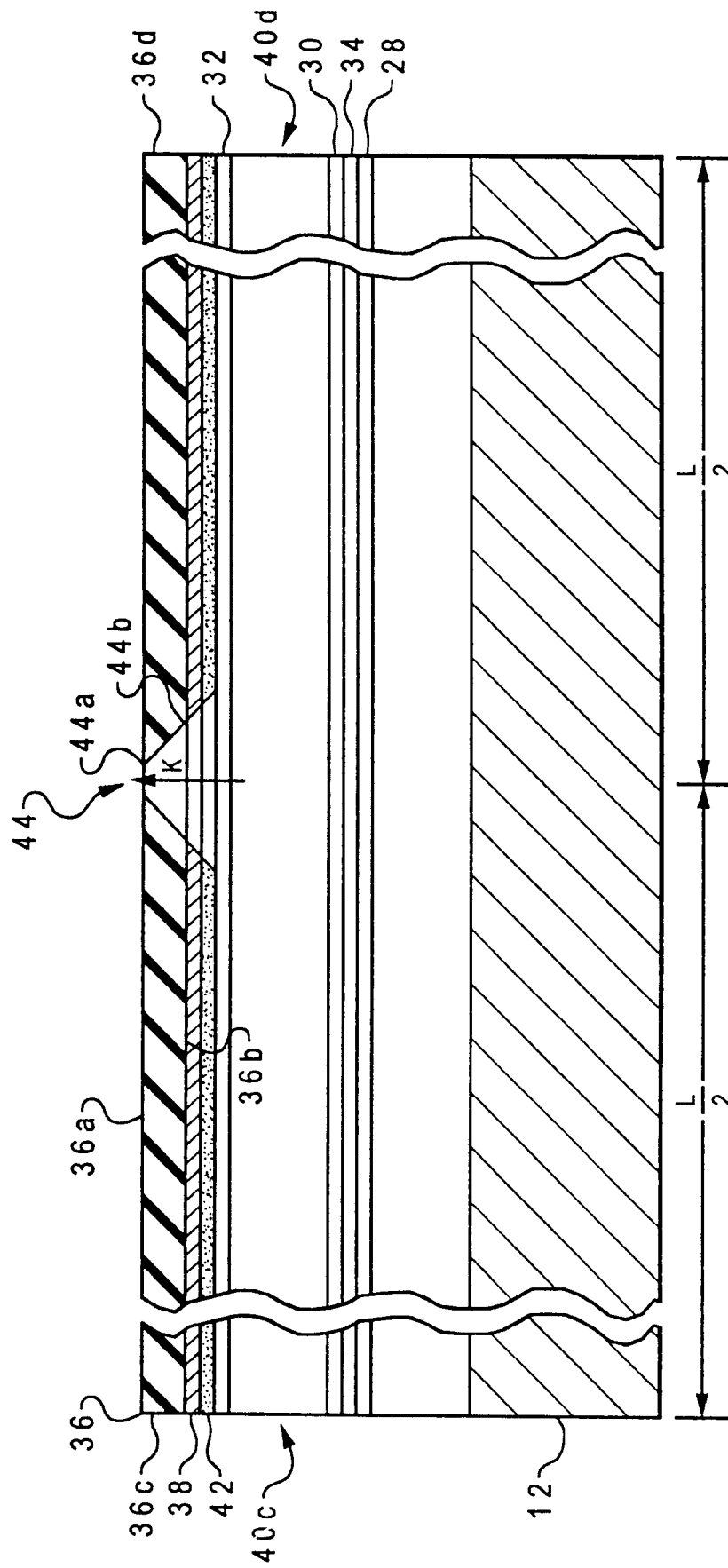


Fig. 3

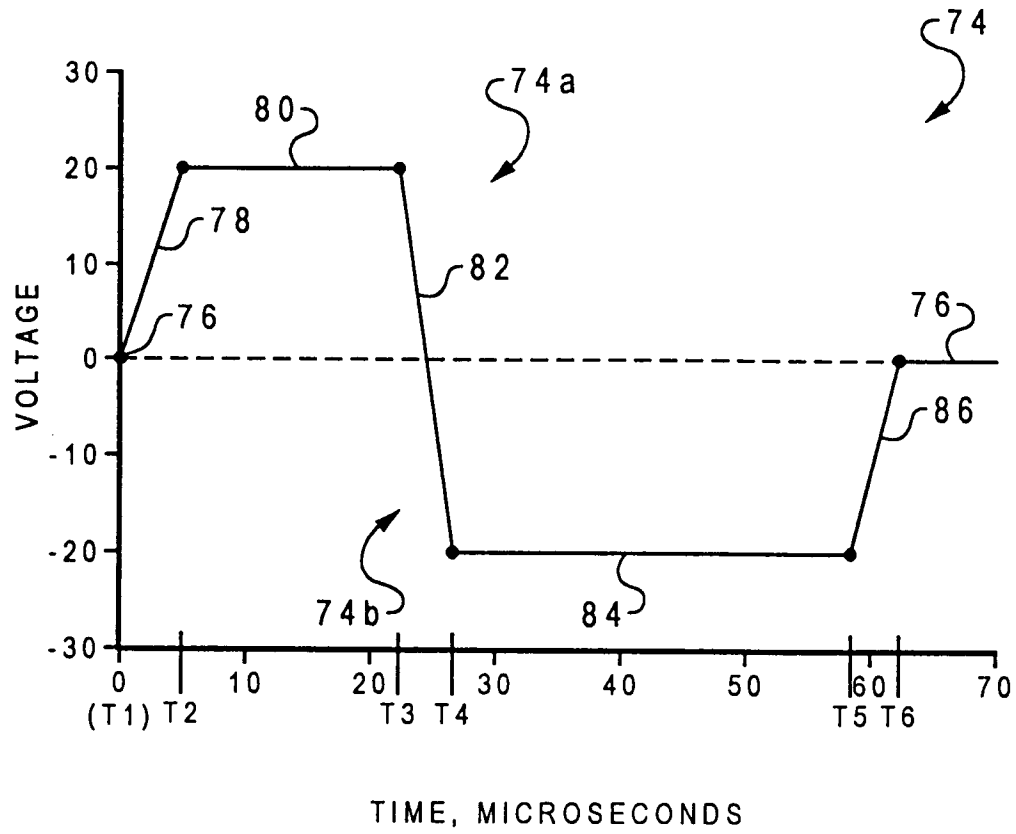


Fig. 4

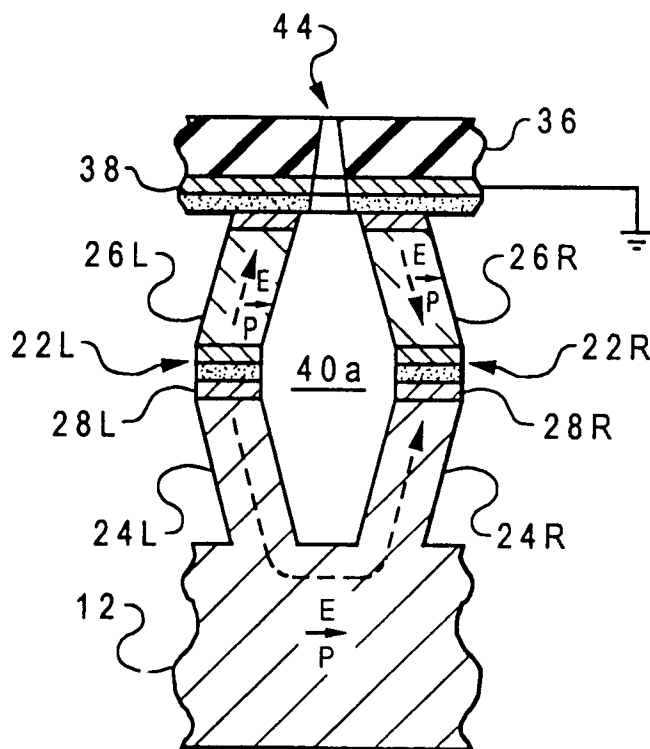


Fig. 5