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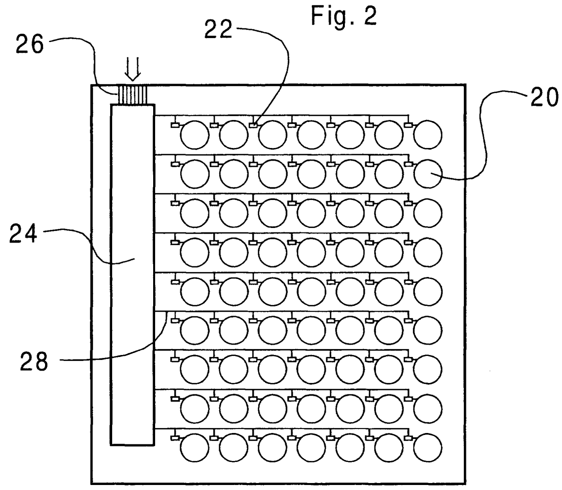
(54) Digital loudspeaker

(57) A digital loudspeaker responsive to a binary digital audio signal received at an input (26). The digital loudspeaker is manufactured as an integrated module comprising an array of acoustic output transducers each with a diaphragm (20) including a conductive layer arranged facing a further conductive layer across a gap. The conductive layers of each transducer form a parallel plate capacitor so that a drive signal applied across the capacitor induces electrostatic force between the capacitor plates, thereby driving the diaphragm (20). The non-linear response of the diaphragms (20) is compensated for by pulse shaping circuits (22) which are arranged adjacent the associated diaphragms (20). The pulse shaping circuits (22) each receive a unary digital drive signal from an encoder circuit (24) via tracks (28). The encoder circuit (24) serves to convert the binary digital audio signal received at the input (26) into a large number of unary digital drive signals, one for each of the output transducers. Using standard silicon processing technology, the entire integrated loudspeaker module, including transducers and drive circuitry, can be integrated onto a single silicon wafer, or two wafers arranged facing each other. In this way, arrays of a thousand transducers or more can be manufactured in a single integrated module of modest total area.

Fig. 2



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Description

[0001] The invention relates to digital loudspeakers, more especially but not exclusively to a digital loudspeaker suitable for generating sound output in response to a unary digital drive signal.

BACKGROUND OF THE INVENTION

[0002] Many digital loudspeaker designs have been previously proposed based on the use of binary digital coding of the signal used to drive the output transducers. As an alternative, in PCT/GB96/00736, the inventor Anthony Hooley proposes the use of unary digital coding instead of the more familiar binary digital coding to drive the output transducers. Potentially, unary digital coding offers an advantage over binary digital coding for driving the output transducers in that artefacts in the sound caused by transients in the drive signal can be eliminated.

[0003] The unary loudspeaker proposed by Hooley is designed to operate with a conventional binary digital input signal which is converted into unary digital form prior to supply to the transducers by a binary-to-unary encoder. The output transducers are then driven by a unary drive signal based on the output of the encoder. One example given is a unary digital loudspeaker for reproducing sound from a 10-binary digit (i.e. bit) digital audio signal.

[0004] The unary loudspeaker proposed by Hooley comprises a plurality of substantially identical output transducers each operative to convert one of a plurality of unary digital signals into a sound pulse so that the cumulative effect of the output transducers is to produce an output sound representative of the input signal. To have equal weight, all the transducers need to be the same. In practice, since there are a large number of output transducers and since each are intended to have equal weight, differences between the transducers will average out, so that errors caused by transducer non-uniformity will not be cumulative, but will rather tend to cancel out statistically. This is another advantage over binary digital coding in which transducers driven by the different order bits must be precisely matched.

[0005] Because of the fact that all output transducers carry equal weight in the unary scheme, a large number of acoustic output transducers will generally be needed for audio reproduction of speech or music with adequate quality. In general, to reproduce an n-bit binary signal 2^n-1 output transducers will be needed. This number can be almost halved to 2^{n-1} output transducers if bipolar driving techniques are used. The overall number of output transducers will thus generally be high for most, if not all, practical implementations of a unary digital loudspeaker. For example, to reproduce a 10-bit digital audio signal, 1023 or 512 output transducers are required, depending on whether bipolar drive signals are used. In the case of a 12-bit digital audio signal, these numbers would rise to 4095 and 2048. Further, for a 16-bit digital audio signal, 65535 or 32768 output transducers would be required. The large number of identical, or at least similar, output transducers is an inherent feature of a unary loudspeaker and is fundamental to its potential advantage over a binary loudspeaker.

[0006] What is needed for effective commercial implementation of a unary loudspeaker is the ability to manufacture large quantities of output transducers at acceptable cost.

[0007] In PCT/GB96/00736 it is suggested that suitable acoustic output transducers could be based on conventional electrostatic transducers, piezo-electric transducers or electromagnetic transducers, since these are capable of being integrated and could be arranged in an array.

[0008] In respect of electrostatic output transducers, it is stated that it would be possible to produce a large number of electrodes of equal area, each with a separate connection to separate unary digital signals, on one physical transducing device.

[0009] In respect of piezo-electric output transducers, it is stated that one piece of piezo-electric material could be divided up into a large number of equal area regions each with its own electrode for separate connection to distinct unary digital signals, again resulting in a transducer array.

[0010] In respect of electro-magnetic output transducers, it is stated that a set of separate connected wires each producing identical ampere-turn effects within the magnetic field of the device, and individually connected to distinct unary digital signals, would again result in a transducer array.

[0011] All such array structures are said to have the great advantage of requiring multiple identical elements which is said to assist with matching and simpler manufacture.

[0012] However, PCT/GB96/00736 contains no further detail on how a suitable acoustic output transducer might be constructed in the numbers required.

[0013] It is thus an object of the invention to provide an acoustic output transducer which can meet the requirements of a unary digital loudspeaker.

SUMMARY OF THE INVENTION

[0014] According to a first aspect of the invention there is provided a digital loudspeaker module comprising a substrate on which is formed an array of acoustic output transducers, and a drive circuit. The drive circuit has an input for receiving a digital audio signal and a plurality of drive signal outputs electrically connected to respective ones of the acoustic output transducers to supply drive pulses to the transducers. Each of the transducers includes a first conductive layer adjacent the substrate and a second conductive layer suspended above the first conductive layer across a gap. At least part of the second conductive layer forms a movable diaphragm. Moreover, the first and second conductive layers are electrically connected to respective ones of the outputs of the drive circuit so that each transducer forms a capacitor in the drive circuit. In use, responsive to the drive pulses supplied by the drive signal outputs, electrostatic forces are generated between the first and second conductive layers that induce motion of the diaphragms to generate sound output.

[0015] It is therefore possible to utilise standard silicon processing technology to provide an integrated loudspeaker module with a large number of acoustic output transducers with associated unary drive circuitry. For example, a single module can be provided which has 2^{10}-1 or 2^{12}-1 acoustic output transducers, sufficient for the reproduction of speech or music to a reasonable quality with the output transducers being driven by unary digital drive signals.

[0016] Because it is possible to make arrays of large numbers of transducers with a small overall area, the problems associated with spatial extent of the transducer array discussed in PCT/GB96/00736 do not arise. For the same reason, the complex, time lag system suggested in PCT/GB96/00736 to compensate for a large spatial extent of the loudspeaker is unnecessary. Indeed, even if a large area array is required for large volume power output, this can be made up of many sub-groups of transducers, each sub-group reproducing the full sound content.

[0017] The ability to integrate the large number of transducers required for unary drive signals into a small area means that unary digital loudspeakers can be employed in applications such as hand-held telephones, especially hand-held video telephones which are held at arms' length by the user in order to view the video image. It is generally problematic to use acoustic output transducers based on conventional binary digital drive signals for such applications owing to the distance between the apparatus and the user's ears. Conventional hand-held telephones rely on the proximity and alignment of the acoustic output transducers to the ear, neither condition being met with a hand-held video telephone.

[0018] In one embodiment of the invention there is provided a digital loudspeaker comprising a plurality of acoustic output transducers and a drive circuit. The drive circuit has an input for receiving a digital audio signal and a plurality of outputs connected to respective ones of the acoustic output transducers. The acoustic output transducers are constructed from a lower panel and an upper panel spaced apart by electrically insulating material. Each transducer includes a first conductive layer in or on the lower panel and a second conductive layer in or on the upper panel, the first and second conductive layers of each transducer being arranged to form respective first and second plates of a capacitor. At least one of the outputs of the drive circuit is connected across the first and second conductive layers of each transducer for supplying a drive signal thereto. The second conductive layer of each transducer extends over a diaphragm portion of the upper panel which is suspended above the lower panel by a resilient support portion of the upper panel. The diaphragm portion of each transducer is movable responsive to electrostatic forces induced by application of a drive signal across the first and second conductive layers by one of the outputs of the drive circuit connected thereto, thereby to generate a pressure pulse.

[0019] In another embodiment of the invention there is provided a digital loudspeaker comprising a semiconductor substrate, or a substrate on which is formed a semiconductor layer (for example silicon-on-sapphire). An array of acoustic output transducers and a drive circuit are then formed in the semiconductor material. Each of the transducers includes a first conductive layer adjacent the substrate and a second conductive layer suspended above the first conductive layer across a gap, the conductive layers being epitaxial layers formed on the semiconductor substrate or underlying semiconductor layer. The conductive layers are connected as for the above-described embodiment and the drive circuit is preferably an integrated circuit formed in the semiconductor material.

[0020] According to a further aspect of the invention there is provided a method of operating a digital loudspeaker module comprising an array of acoustic output transducers, and a drive circuit having an input for receiving a digital audio signal and a plurality of drive signal outputs electrically connected to respective ones of the acoustic output transducers to supply drive pulses thereto. Each transducer constitutes a capacitor in the drive circuit and has an upper plate and a lower plate, the conductive material of the upper plate forming part or all of a membrane. The method comprises the steps of:

receiving a sample of a digital audio signal at the drive circuit input;
analysing the sample in an encoder part of the drive circuit to determine a subset of the transducers to actuate for that sample; and
actuating the transducers of the determined subset of transducers by supplying respective drive pulses across the upper and lower plates of the transducers concerned, wherein the upper plates of the capacitors are contiguous with resiliently-supported solid-state membranes suspended above the lower plates of the capacitors.

[0021] In this method, the drive pulses are preferably shaped in a pulse shaping part of the drive circuit to compensate for pre-determined non-linear response characteristics of the resiliently-supported solid-state membranes that form the respective upper plates of the capacitors.

[0022] In some embodiments of the digital loudspeaker module, the drive circuit is configured to receive a conventional binary digital audio signal and convert it into unary form for driving the acoustic output transducers. In other embodiments, the drive circuit is configured to receive a digital audio signal that is already in unary form. In still further embodiments, the drive circuitry drives the transducers with more independence than in binary drive circuitry, but with less independence than a pure unary drive circuitry in which each transducer is fully independently drivable. Drive circuitry of this kind, intermediate between binary and unary drive circuitry, is referred to as subbinary drive circuitry in the following. Such subbinary drive circuitry is believed to be novel and inventive.

[0023] Consequently, according to a further aspect of the invention, there is provided an integrated digital loudspeaker module comprising an array of between 2^n and 2^{n+1} acoustic output transducers, where n is not less than 4 or 5, and drive circuitry including an input for receiving a digital audio signal and output lines arranged to provide an independent drive capability to a number of groups of the transducers, where said number is less than 2^{n-1} but more than twice n.

[0024] Still further, although the present invention is directed principally to providing a digital loudspeaker that uses unary or subbinary digital coding for driving the output transducers, it will be understood that the invention can also be embodied as a digital loudspeaker that uses conventional binary digital drive circuitry in combination with arrays of transducer elements fabricated as hereinbelow described.

[0025] The movable diaphragms may be connected by resilient supports to respective laterally adjacent parts of the module, the resilient supports providing restoring forces for the diaphragms in respect of the electrostatic forces generated by the drive signals. Further, the resilient supports and the diaphragms are formed integrally with each other in some embodiments, i.e. from a common piece of material, the resilient supports being thinned regions of that material.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] For a better understanding of the invention and to show how the same may be carried into effect reference is now made by way of example to the accompanying drawings in which:

Figure 1 shows in section an acoustic output transducer used in an embodiment of the invention;

Figure 2 shows in plan view an integrated module of 2^6-1=63 of the acoustic output transducers of Figure 1 together with drive circuitry including an encoder circuit and pulse shaping circuits;

Figure 3 shows a portion of the module of Figure 2 in more detail;

Figure 4 shows structure of the encoder circuit of Figure 2 including sub-modules for converting 3-bit binary digital input into a 7-channel unary digital output;

Figure 5 shows logic gates of one of the sub-modules shown in Figure 4;

Figures 6A to 6F show schematically in section an area of a silicon wafer during processing to form an acoustic output transducer according to another embodiment of the invention;

Figure 7 shows a digital signal processor comprising digital-to-unary converter and pulse shaping circuitry used in a further embodiment of the invention; and

Figures 8A and 8B show in plan view respectively upper and lower parts of an integrated module of 8-by-8, i.e. 64, acoustic output transducers according to another embodiment of the invention using alternative drive circuitry.

DETAILED DESCRIPTION

[0027] Figure 1 shows in section an acoustic output transducer used in one embodiment of the invention.

[0028] Referring to Figure 1, each transducer comprises a lower panel 1 and a upper panel 2. The panels 1 and 2 are arranged parallel to each other and spaced apart by insulating material 3 with a separating gap 4 being formed between a lower side 5 of the upper panel and an upper side 6 of the lower panel. The panels 1 and 2 are based on silicon wafers and the insulating material is a polymer insulator arranged in pillars extending between the panels. In other embodiments, the insulating material 3 could be formed from the material of the upper or lower panels. Manufacture of an integrated transducer array based on transducers according to the transducer of Figure 1 is described in more detail further below.

[0029] The lower panel 1 has a conductive layer 7 in the form of a metal layer, for example metal or highly-doped semiconductor, arranged on an lower side 8 thereof. The upper panel 2 has a conductive layer 9 in the form of a metal layer or a layer of highly-doped semiconductor, arranged on an upper side 10 thereof. The conductive layers 7 and 9 are positioned a distance 'd' apart and, for the loudspeaker drive circuit described further below, form first and second plates of a parallel plate capacitor. The conductive layers 7 and 9 are provided with respective tracks (not shown) via which a drive signal is applied to the transducer in use. The tracks may for example be of standard silicides or metal such as gold, aluminium or copper.

[0030] The upper panel 2, at each transducer, has a waisted bridge portion 18 interconnecting a thicker peripheral portion 19 and a thicker central diaphragm portion 20. The waisted bridge portion 18 is sufficiently thin that the diaphragm portion 20 is resiliently supported relative to the peripheral portion 19. In the present embodiment, the diaphragm portions 20 of the module are circular, the resilient support portions 18 are ring-shaped and the peripheral portions occupy a square area. However, it will be understood that the shape of the diaphragm portions may be varied and is not fundamental to performance of the transducer elements. For example, oval, square or rectangular diaphragms could be used instead of circular ones.

[0031] In use, application of a drive signal to the conductive layers 7 and 9 will generate electrostatic forces of attraction (and repulsion) between the lower panel 1 and upper panel 2 to which the conductive layers 7 and 9 are adhered. The effect of the electrostatic forces is to move the diaphragm portion 20 of the upper panel 2 relative to the lower panel 1, through deformation of the resilient support portion 18.

[0032] The electrostatic attractive force F_x induced between the conductive layers 7 and 9 by the drive signal is given by $F_x = - ½ \varepsilon (V^2 /d^2) A$. The parameter ε is the dielectric permittivity, which will be a compound value taking account of the fact that the gap 'd' will generally be part air or vacuum, and part silicon or other wafer material. The parameter V is the applied voltage of the drive signal which will be a function of time V(t), typically in the form of drive pulses. The parameter A is the effective area of the parallel plate capacitor formed by the conductive films. The relevant area for the equation of motion for the diaphragm will be the movable area of the transducer, i.e. the area of the diaphragm portion 20.

[0033] The transducer can be viewed as a forced harmonic oscillator in which the applied drive force is that induced electrostatically by the drive signal V(t). The resilient support portion 18 provides a restoring force with a spring constant 'k', the value of which will depend on its dimensions and mechanical properties. The equation of motion (with no damping term) for the transducer is then:

$$m\, d^2x/dt^2 + kx = F_x = - ½\, \varepsilon\, (V(t)^2 /d^2)\, A.$$

[0034] A damping term (b dx/dt) can be added to the left-hand side of the above equation if appropriate, for example to take account of air viscoscity. Conventional diaphragm modelling techniques can then be applied to calculate what shape of drive pulse will produce a linear, or more approximately linear, response of the diaphragm portion 20. For this purpose, a pulse shaping circuit may be included, as is described further below.

[0035] To manufacture an integrated module of multiple transducers, two silicon wafers are taken as a starting point, one for the lower panel 1 and another for the upper panel 2. The silicon wafers may, for example, be 5 inch diameter wafers (5 inches amounts to approximately 12.5 cm) having a thickness of 625 micrometers. Any other industry-standard diameter could conveniently be used.

[0036] To manufacture the upper panel 2, a wafer is etched from the upper side 10 to thin over a circular area which will form the upper side of the resilient support and diaphragm portions 18 and 20 of each transducer. The wafer is then etched from the lower side 5 over a ring area to form a thinned bridge for the resilient support portion 18. The thickness in section of the resilient support portion 18 may be chosen to provide any desired characteristic spring constant. For example, the thickness may be in the range 5 to 100 micrometers, or beyond. One specific value is 20 micrometers. The thickness chosen will depend on the mass, and thus inertia, of the diaphragm portion 20. The thickness chosen will also depend on the radial dimension of the resilient support portion 20. The diaphragm portion 20 will generally be thicker than the resilient support portion 18, but this is not necessarily the case. The thickness of the diaphragm portion 18 will be relevant for the definition of the mass 'm' of the moving part of the transducer in the above equation of motion. One specific value for the thickness of the diaphragm portion is 300 micrometers. After etching, masking nitride and oxide layers are removed and the wafer can be metallised on its upper side 10 to form the conductive layer 9. A protective coating of PECVD nitride is then added (not shown).

[0037] To manufacture the lower panel 1, conductive layer 7 is applied to one side of a wafer by metallisation and a PECVD nitride layer (not shown) is added. Polymer insulator posts 3 are then applied by deposition and patterning to the other side of the wafer. The deposition and patterning can use photo-imageable polyimide. The posts may be from 10 micrometers to 50 micrometers in height, or higher, for example between 50 and 500 micrometers in height. The height of the posts is preferably chosen so that, in the finished device, the lower side 5 of the diaphragm portion of the upper panel can physically contact the upper side 6 of the lower panel 1 without fracture or permanent damage to the resilient support portion 18 which deforms responsive to the drive signal. In this way, the transducer has some inherent protection against being overdriven.

[0038] The lower panel 1 and upper panel 2 are then joined together using standard alignment and bonding procedures.

[0039] With the arrangement of the conductive layers 7 and 9 in the present embodiment, the first and second conductive layers remain spaced apart even if the diaphragm portion of a transducer is brought into physical contact with the lower panel by overdriving. This ensures that no electrical short can occur across the plates of the capacitor as a result of such contact.

[0040] This function can be achieved with a number of arrangements of the conductive layers, not just that of the present embodiment. For example, it is achieved if the first conductive layer 7 is formed in or under the lower panel 1 remote from the upper side 6 of the lower panel facing the upper panel 2. It is also achieved if the second conductive layer 9 is formed in or on the upper panel 2 remote from the underside 5 of the diaphragm portion 20 facing the lower panel 1.

[0041] In the present embodiment, the above-described transducer is part of a transducer array formed as an integrated module.

[0042] Figure 2 and Figure 3 show in plan view an integrated module comprising a 9-by-7 array of 2^6-1=63 transducers. Each transducer has a square footprint with a centrally-arranged circular diaphragm, the array being formed as a square grid.

[0043] Adjacent the diaphragm 20 of each transducer, there is provided drive circuitry in the form of a pulse shaping circuit 22. The pulse shaping circuit 22 is designed, having regard to a non-linear response function for the diaphragm computed from the above equation of motion, so that a standard square-shaped input pulse received by the pulse shaping circuit is transformed into a non-square pulse shape that at least partially compensates for the non-linear diaphragm response, thereby to produce an acceptably uniform acoustic pulse output pressure.

[0044] For example, if the resilient portion is shaped and dimensioned to provide a relatively large spring constant 'k', then restoring forces will dominate the diaphragm response in which case the pulse shaping circuit 22 can be designed to provide a ramp at the start of each drive pulse.

[0045] On the other hand, if the diaphragm portion 20 is made relatively large in comparison with the resilient support portion 18, then inertial forces may dominate the diaphragm response in which case sharp pulses can be inserted at the beginning and end of each drive pulse to initiate and arrest diaphragm motion.

[0046] Pulse shaping considerations in both these instances are described more fully in PCT/GB96/00736.

[0047] Whether restoring forces or inertial forces dominate, non-linear contributions from the variance of the gap 'd' may also be significant and require compensation by pulse shaping. Moreover, the diaphragm response may be further varied by provision of a viscous medium, such as a liquid or gas, in the space between the diaphragm and lower panels 1 and 2, thereby providing a further design parameter.

[0048] The module's pulse shaping circuits 22 are formed in the peripheral portions 19 of the silicon upper panel 2 of each transducer as integrated circuits, using standard photolithographic patterning techniques. Alternatively, the pulse shaping circuits and other drive circuitry could be formed in the lower panel 1 in another embodiment.

[0049] Nine groups 28 of seven tracks form the 63 unary outputs of the encoder circuit 24, each group 28 extending to supply the transducers of one of the nine rows of the transducer array. Each track terminates in a spur contacting to the input of one of the pulse shaping circuits 22.

[0050] In an alternative embodiment, there is provided one pulse shaping circuit for each row or pairs of rows of transducers, with the drive pulses for each row all being routed through the associated pulse shaping circuit. In this case, the pulse shaping circuit output could be connected to all of the transducers of its row or pair of rows. A column selector circuit would then be arranged to selectively connect the output of each pulse shaping circuit to any one of the associated transducers, responsive to an input to the selector circuit supplied by the encoder circuit. There would thus be an addressing scheme somewhat similar to that used in displays or CCD detectors.

[0051] Returning to Figure 2, to one side of the transducer array there is provided further drive circuitry in the form of a binary-to-unary encoder circuit 24. The encoder circuit 24 is formed as an integrated circuit in a lateral extension of the silicon upper panel 2 using standard photolithographic patterning techniques. The encoder circuit 24 has an input 26 for receiving a 6-bit binary digital audio signal. The encoder circuit is made up of a unipolar logic gate array. Alternatively, offset or two's-complement types of logic may be used, as described in PCT/GB96/00736.

[0052] Figure 4 shows the structure of the encoder circuit 24 in more detail. The six tracks of the 6-bit binary digital input 26 are connected to a binary-to-binary converter 30 which converts the 6-bit binary digital input into nine 3-bit binary digital outputs 32. In making this conversion, the three least significant bits form one of the 3-bit outputs. The 4th least significant bit forms another of the 3-bit outputs, the 5th least significant bit forms a further two of the 3-bit outputs and the 6th least significant bit forms the remaining four 3-bit outputs. The nine 3-bit outputs are connected to respective encoder submodules in the form of unipolar 3-bit binary-to-unary converters 34, each for providing seven unary digits of output which are supplied to respective rows of the transducers in the track groups 28 already mentioned with reference to Figures 2 and 3. The converters 34 are clocked by a clock signal CLK to ensure synchronisation of their outputs. The clock signal may be generated internally by the transducer module or may be received as part of, or derived from, the input signal 26.

[0053] The encoder circuit 24 is configured so that in use the currently active transducers, i.e. those connected to outputs of the encoder circuit that are carrying drive signals, are clustered generally in a cohesive active area, preferably an area in a mid-region of the array. As the sound level is increased, the encoder circuit is configured to select for driving previously inactive transducers lying adjacent the previously active area, so as to maintain the generally cohesive nature of the active area. Similarly, as the sound level is decreased, transducers are removed from the edge of the previously active area. It will however be understood that a proportion of the active transducers, preferably a small proportion, may be physically remote from the active transducers that collectively form a generally cohesive area.

[0054] Figure 5 shows the logic gate structure of one of the unipolar 3-bit binary-to-unary converters 34. The other converters 34 are the same. There are three input lines 35 for the 3-bit binary digital input, the input lines 35 being collectively referred to using the reference numeral 32 in Figure 4. The upper one of the illustrated three input lines is for the most significant bit of the 3-bit input. The lower one of the three illustrated input lines is for the least significant of the three bits. The seven unary output lines 36 collectively form one of the groups 28 illustrated in Figure 4, and also Figure 2 and Figure 3.

[0055] With a transducer footprint area of 1-by-1 centimeters, the above-described module with 63, i.e. 2^6-1, transducers can be made from a single pair of 5 inch wafers. With a footprint of 2.5 millimeters square a module with 2^8-1 transducers can be made using a pair of 5 inch wafers. In some embodiments, each module will have 2^n, 2^{n-1} or 2^n-1 transducers to be compatible with the unary reproduction of a conventional n-bit binary digital audio signal. In other embodiments, different numbers of transducers may be provided through the use of power control as described in PCT/GB96/00736.

[0056] By using conventional silicon micromachining and other conventional silicon processing techniques, it is possible to vary the area of each transducer through several orders of magnitude without changing the basic design. For example, the individual length dimension of each transducer could be 10 millimeters or 0.1 millimeters. With an individual transducer area of 0.1-by-0.1 millimeter, a transducer array of 2^{16}-1 output transducers would occupy a total area of 2.2cm-by-3cm for example. This scalability, together with the highly reproducible nature of silicon technology, means that almost any practically desirable number of output transducers can be integrated into a single module of a pre-defined total area.

[0057] In addition it is possible to incorporate all the drive circuitry in the panels, more preferably with all or substantially all of the drive circuitry in only one of the two panels, with the other of the panels having a single conductive layer for all transducers that is electrically connected to earth.

[0058] As well as semiconductor materials, insulator materials such as sapphire could also be used for the panels. For example, a sapphire lower panel could be used in combination with a silicon upper panel with the drive circuitry primarily incorporated in the upper panel.

[0059] For smaller transducers, photolithographic techniques common for integrated circuits could be employed instead of the large scale micro-machining techniques described above. Moreover, instead of two wafers, the loudspeaker module could be manufactured from a single wafer with the space between the upper and lower panels being formed by selective etching.

[0060] One such embodiment is now described with reference to Figure 6A to Figure 6F which show in sequence fabrication steps of an acoustic output transducer used in another embodiment of the invention, by schematic illustration of cross-sections through a wafer during various stages of processing. The formation of only one transducer element is illustrated, but it will be understood that a large two-dimensional array of similar transducers will typically be fabricated.

[0061] Figure 6A shows a conducting n++ Silicon substrate on which has been deposited a sacrificial layer of silicon dioxide.

[0062] Figure 6B shows the structure of Figure 6A on which has been patterned a layer of resist after etching to remove portions of the sacrificial oxide layer that are distributed around an area which is ultimately to form the diaphragm of a single transducer element.

[0063] Figure 6C shows the structure of Figure 6B after deposition of intrinsic silicon, which is an insulating material, and subsequent removal of the resist shown in Figure 6B. The intrinsic silicon is deposited to form a ring of insulating pillars (when viewed from above) around an area which will form the diaphragm in the finished device.

[0064] Figure 6D shows the structure of Figure 6C after patterning with a further layer of resist, the resist leaving an open area somewhat smaller than and concentric with the enclosed area defined by the intrinsic silicon pillars, and subsequent etching to remove an upper part of the area of silicon dioxide that remains exposed, thereby to thin the silicon dioxide layer over this area.

[0065] Figure 6E shows the structure of Figure 6D after removal of the resist and deposition of a thick layer of metal covering the thinned area of silicon dioxide and extending laterally to cover the intrinsic silicon pillars.

[0066] Figure 6F shows the structure of Figure 6E after removal of the remaining parts of the sacrificial silicon dioxide layer to form the final structure of the transducer element (except for structure associated with subsequent metallisation, passivation etc. which is not shown).

[0067] Figure 6F is additionally provided with reference numerals corresponding to those used in Figure 1 and showing elements of the transducer. The n++ substrate forms a lower panel 1 which is conductive so that provision of a separate conductive layer is not necessary. The metal layer forms the upper panel 2. The intrinsic silicon pillars form the insulating material 3. A gap 4 is formed by the space left after etching away the remainder of the sacrificial silicon dioxide layer and is bounded on its upper side by the metal layer and on its lower side by the substrate. The metal layer has a thicker central area forming the diaphragm portion 20, regions laterally coextensive with the pillars 3 which form the peripheral portion 19 and a ring-shaped region lying radially adjacent and within the pillars 3 which form the resilient support portion 18 of the transducer.

[0068] It will be understood that although the above description of Figure 2 and Figure 3 was made with reference to a transducer according to Figure 1, the description of these figures applies also to a transducer according to Figure 6F which can be used in a module structure as shown in Figure 2, although much larger numbers of transducers would be fabricated in a typical example of transducers according to Figure 6F.

[0069] Transducer drive circuits may be integrated circuits formed in the semiconductor material of the transducer array using conventional processing techniques. This is possible with an array made of transducers as described with reference to Figure 1 or Figure 6F. Moreover, the transducer drive circuits may be distributed among the transducer elements, laterally adjacent the array, or partly among the transducer elements and partly laterally adjacent the array.

[0070] Although one specific implementation in silicon using photolithographic techniques has been described, it will be understood that considerable variation is possible. For example the substrate 1 may include an intrinsic layer on its upper side to prevent physical contact by the metal layer causing an electrical short of the capacitor. The substrate may also be insulating rather than conductive and have a conductive layer, such as a metal layer on its underside for forming one plate of the parallel plate capacitor. Moreover, the upper layer 2 may include silicon, silicon dioxide or silicon nitride as well as, or instead of, metal. Many other variations will be apparent.

[0071] Further, as an alternative to silicon technology, GaAs technology could be used. For example, the lower side 5 of the upper panel 2 and the upper side 6 of the lower panel could be the lower and upper surfaces of respective GaAlAs epitaxial layers, with the gap 4 being formed by selective lateral dry etching of an intervening GaAs layer using CCl_2F_2. Details of this etch process are given in an article by Martin Walther *et al* in Journal of Applied Physics, volume 72, 2069 (1992). In this case, it will be understood that references to upper and lower panels will be references to upper and lower portions of semiconductor material originating in the same wafer, with the lower portion being lower epitaxial layers, or the substrate itself, and the upper portion being etched upper parts formed from epitaxial layers.

[0072] Some common design constraints for the integrated loudspeaker module of many embodiments will be the total area permitted for the transducer array, the number of bits of resolution (from which follows the number of transducers required) and the output power capability. The shape of the integrated module may also vary depending on the application. For example, for a hand-held video telephone, the transducer modules may be rectangular strips for arrangement on adjacent sides of a display panel.

[0073] It will be understood that although it will be convenient and desirable in most cases to manufacture the transducers in integrated modules. However, it is also possible to manufacture the transducers singly should this ever be required. In a typical application, a loudspeaker will be made from one integrated module or a relatively small plural number of modules, for example between 2 and 10 modules.

[0074] Figure 7 shows schematically a digital signal processor 40 used in an alternative embodiment arranged to one side of the transducer array. The digital signal processor forms a part of the drive circuit including binary-to-unary encoding circuitry 24 arranged to receive a binary digital input 26 and pulse shaping circuitry 22 arranged to modify the shape of each drive pulse prior to routing of that pulse to one of the drive signal outputs 28.

[0075] To perform binary-to-unary encoding, the digital signal processor 40 is loaded with a binary-to-unary conversion routine for determining which drive circuit outputs receive drive pulses responsive to the binary digital audio signal. The conversion routine can be based on a look-up table or may incorporate an algorithm. In this regard, it is noted that no addressing in a conventional sense is required for the unary outputs, because each output has equal significance.

[0076] To perform the pulse shaping function, the digital signal processor 40 is loaded with a pre-determined non-linear response function or characteristic of the transducers, and is operable to compute the output pulse shapes of the drive pulses based on this response.

[0077] It will be understood that separate digital signal processors could be used for encoding and pulse shaping. Further, only one of these processing functions could be performed with a digital signal processor, the other being implemented in dedicated integrated circuits.

[0078] Figure 8A and Figure 8B show an integrated module according to another embodiment of the invention which uses alternative drive circuitry. Illustrated is an 8-by-8 array of 64 acoustic output transducers. Figure 8A shows an upper part of the module with circular diaphragms and associated upper conductive layers 9, whereas Figure 8B shows a lower part of the module with lower conductive layers 7. The arrangement of digital audio signal input 26, encoder 24, and the general layout of the transducers, will be understood by reference to the above-described embodiments. The present embodiment may be based on transducers according to Figure 1 or Figure 6F.

[0079] As shown in Figure 8A, in this embodiment, the drive circuitry includes an additional component in the form of a column select circuit 25 connected to receive address data from the encoder circuit 24 which may be a microprocessor, more especially a digital signal processor. Selection lines 38 connect the column select circuit 25 with the upper conductive layers 9 of the transducers. Illustrated are eight separate selection lines 38 to the upper conductive layer 9 of each individual transducer of columns 1 and 8, four separate selection lines 38 to the upper conductive layers 9 of adjacent pairs of transducers in columns 2 and 7, two selection lines 38 to the upper conductive layers 9 of two groups of four transducers in columns 3 and 6, and a single selection line 38 to the upper conductive layers 9 of all the transducers in each of columns 4 and 5. With this arrangement, in the absence of a column select signal to any given upper conductive layer, that layer is open circuited so that it will float to follow the facing lower conductive layer, thereby suppressing any voltage differences which would tend to cause diaphragm motion.

[0080] As shown in Figure 8B, the module of this embodiment includes one pulse shaping circuit 22 for each row of transducers. The pulse shaping circuits 22 are each individually connected to an output of the encoder circuit 24 by a connection line 39. The lower conductive layers 7 of the transducers of each row are electrically connected to each other, as illustrated by an elongate rectangular area in Figure 8B, and to the output of the pulse shaping circuit 22 for the row concerned.

[0081] In this way, a given individual transducer element is driven by an electrostatic driving force to output sound only when there is an appropriate combination of a drive signal to its row through the relevant one of the pulse shaping circuits 22 and a select signal to its upper conductive layer 7.

[0082] It will be understood that the drive capability for each row signal output from the associated pulse shaping circuit 22 needs to be sufficient to drive the maximum load presented by the transducers of that row.

[0083] With the cross-point addressing scheme of the present embodiment, in comparison with the drive circuit arrangement shown in Figures 2 and 3, there is the advantage that the number of pulse shaping circuits is reduced from one per transducer to one per row of transducers. Further, the use of separate column and row select lines allows the total number of interconnect lines over the module to be reduced by connecting together the upper conductive layers of groups of transducers. In the illustrated arrangement, these connections are in 16 groups of 1, 8 groups of 2, 4 groups of 4 and 2 groups of 8 with each group extending in the columnwise direction. However, any desired sub-division of groups may be chosen. For example, there could be one columnwise extending group of each of 1, 2, 4, 8, 16 and 32 transducers in an array of 63 transducers.

[0084] In this respect it will be relevant to consider that to avoid transient problems, analogous to those present in binary schemes, the grouping needs to be such that in use incremental changes in the number of transducers to be driven can be effected across a broad range of total number of active transducers without having to switch on and off a significant proportion of the active transducers. For this reason it is preferred in the present embodiment that the encoder 24 is implemented as a digital signal processor so that the module can be driven having regard to which individual transducers are active to minimise transients between sampling intervals.

[0085] It will thus be understood that the present embodiment will have a number individually drivable transducers less than the total number of transducers of the array, but substantially more than the number of an equivalent binary driven transducer array. This provides an interim subbinary design of drive circuitry which requires less connection lines than pure unary drive circuitry in which each transducer has its own connection lines so that it is fully independently drivable, but has significantly more connection lines than a binary drive circuit and is thus drivable without the major drive transients that occur with a binary drive in which an array of 2^n transducers is subdivided into only n independently drivable transducer blocks of 1, 2, 4, 8 and 2^{n-1} transducers. Preferably, in a transducer array according to the present embodiment comprising at least 2^n transducers, the largest block of collectively driven transducers will comprise no more than 2^{n-3}, more preferably 2^{n-4}, transducers. This compares with a binary driven transducer array of 2^n transducers which the largest block would have 2^{n-1} collectively driven transducers. Moreover, for the same reason, it is preferable if there are a significant number of smaller blocks of transducers, for example a significant number of individually drivable transducers and/or transducer pairs.

[0086] Although the invention has been described above in terms of an embodiment for receiving a 6-bit binary digital audio signal, it will be understood that in practice an integrated transducer module will often be more preferably suitable for processing 8-bit, 10-bit, 12-bit or 16-bit binary digital audio signals. The 6-bit design described above is readily scalable to provide such higher audio resolution, as is needed for a reasonable reproduction quality of content bearing speech or musical signals. In fact, description of a 6-bit embodiment is made herein primarily to assist clarity by avoiding the presence of much higher numbers of transducers which are less amenable to simple graphical representation and should not be taken as an indication that this is an optimum or typical number of transducers for an integrated digital loudspeaker module.

Claims

1. A digital loudspeaker module comprising a substrate on which is formed an array of acoustic output transducers, and a drive circuit having an input for receiving a digital audio signal and a plurality of drive signal outputs electrically connected to respective ones of the acoustic output transducers to supply drive pulses thereto, wherein each of the transducers includes a first conductive layer adjacent the substrate and a second conductive layer suspended above the first conductive layer across a gap, at least part of the second conductive layer forming a movable diaphragm, wherein the first and second conductive layers are electrically connected to respective ones of the outputs of the drive circuit so that each transducer forms a capacitor in the drive circuit, whereby, in use, responsive to the drive pulses supplied by the drive signal outputs, electrostatic forces are generated between the first and second conductive layers that induce motion of the diaphragms to generate sound output.

2. A digital loudspeaker module according to claim 1, wherein the movable diaphragms are connected by

resilient supports to respective laterally adjacent parts of the module, the resilient supports providing restoring forces for the diaphragms in respect of the electrostatic forces generated by the drive signals.

3. A digital loudspeaker module according to claim 2, wherein the resilient supports and the diaphragms are formed integrally with each other from a common piece of material, the resilient supports being thinned regions of that material.

4. A digital loudspeaker module according to claim 1, 2 or 3, wherein the substrate and first conductive layers form part of a lower panel and the second conductive layers and diaphragms form part of an upper panel.

5. A digital loudspeaker module according to claim 4, wherein the upper panel is made of a semiconductor material and the drive circuit is an integrated circuit formed in the upper panel.

6. A digital loudspeaker module according to claim 4, wherein the lower panel is made of a semiconductor material and the drive circuit is an integrated circuit formed in the lower panel.

7. A digital loudspeaker module according to claim 4, wherein the upper and lower panels are made of a semiconductor material and the drive circuit is an integrated circuit formed in the upper and lower panels.

8. A digital loudspeaker module according to claim 1, 2 or 3, wherein the substrate is formed of, or includes a layer of, a semiconductor material and the first and second conductive layers are epitaxial layers formed on the semiconductor material.

9. A digital loudspeaker module according to any one of the preceding claims, wherein the drive circuit is an integrated circuit formed in a semiconductor material of or on the substrate.

10. A digital loudspeaker module according to any one of the preceding claims, wherein the drive circuit includes pulse shaping circuitry configured to modify the drive pulses in the sense tending to equalise pulse output pressure of the transducers during the drive pulses responsive to pre-determined non-linear response characteristics of the transducers.

11. A digital loudspeaker module according to claim 10, wherein the pulse shaping circuitry is part of a digital signal processor loaded with the pre-determined non-linear response characteristics of the transducers and operable to compute output pulse shapes of the drive pulses based thereon.

12. A digital loudspeaker module according to any one of the preceding claims, wherein the drive circuit includes an encoder circuit arranged to receive a binary digital audio signal at the drive circuit input.

13. A digital loudspeaker module according to claim 12, wherein the encoder circuit is arranged to convert the binary digital audio signal received at the drive circuit input into a subbinary digital audio signal which is supplied to ones of the drive circuit outputs.

14. A digital loudspeaker module according to claim 12, wherein the encoder circuit is arranged to convert the binary digital audio signal received at the drive circuit input into a unary digital audio signal, each unary digit of which is supplied to one of the drive circuit outputs.

15. A digital loudspeaker module according to any one of claims 1 to 11, wherein the drive circuit includes an encoder circuit arranged to receive a unary digital audio signal at the drive circuit input.

16. A digital loudspeaker module according to claim 15, wherein the encoder circuit is arranged to convert the unary digital audio signal received at the drive circuit input into a subbinary digital audio signal which is supplied to ones of the drive circuit outputs.

17. A digital loudspeaker module according to claim 15, wherein the encoder circuit is arranged to supply each unary digit of the unary digital audio signal received at the drive circuit input to one of the drive circuit outputs.

18. A digital loudspeaker module according to any one of claims 12 to 17, wherein the encoder circuit is part of a digital signal processor loaded with a conversion routine for determining which drive circuit outputs receive drive pulses responsive to the digital audio signal received at the drive circuit input.

19. A digital loudspeaker module according to any one of the preceding claims, wherein the first and second conductive layers are arranged so that, in the case that one of the diaphragms is brought into physical contact with underlying material by overdriving, the first and second conductive layers remain spaced apart by insulating material, thereby preventing an electrical short across the plates of the capacitor.

20. A digital loudspeaker module according to any one of the preceding claims, wherein said array of output transducers contains between 2^n and 2^{n+1} acoustic output transducers, and wherein the drive signal outputs are electrically connected to respective ones of the acoustic output transducers so as to provide an independent drive capability to a number of groups of the transducers, where said number of groups is less than half 2^n, but more than twice n.

21. A digital loudspeaker comprising an array of between 2^n and 2^{n+1} acoustic output transducers, where n is at least 5, and drive circuitry including an input for receiving a digital audio signal and output lines arranged to provide an independent drive capability to a number of groups of the transducers, where said number is less than 2^{n-1}, but more than twice n.

22. A method of operating a digital loudspeaker module comprising an array of electrostatically operable acoustic output transducers, and a drive circuit having an input for receiving a digital audio signal and a plurality of drive signal outputs electrically connected to respective ones of the acoustic output transducers, each of which forms a capacitor in the drive circuit having an upper plate and a lower plate, the method comprising the steps of:

receiving a sample of a digital audio signal at the drive circuit input;
analysing the sample in an encoder part of the drive circuit to determine a subset of the transducers to actuate for that sample;
actuating the transducers of the determined subset of transducers by supplying respective drive pulses across the upper and lower plates of the transducers concerned, wherein the upper plates of the capacitors are contiguous with resiliently-supported solid-state membranes suspended above the lower plates of the capacitors.

23. A method according to claim 22, wherein the drive pulses are shaped in a pulse shaping part of the drive circuit to compensate for pre-determined nonlinear response characteristics of the resiliently-supported solid-state membranes that form the respective upper plates of the capacitors.

Fig. 1

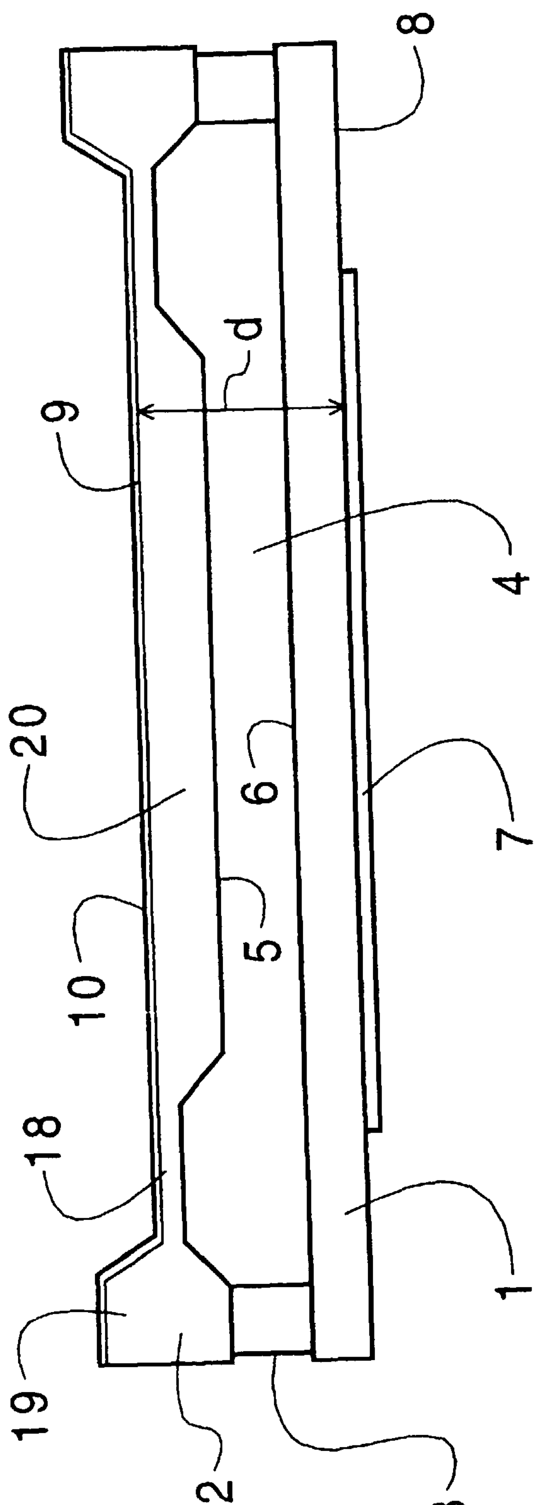


Fig. 2

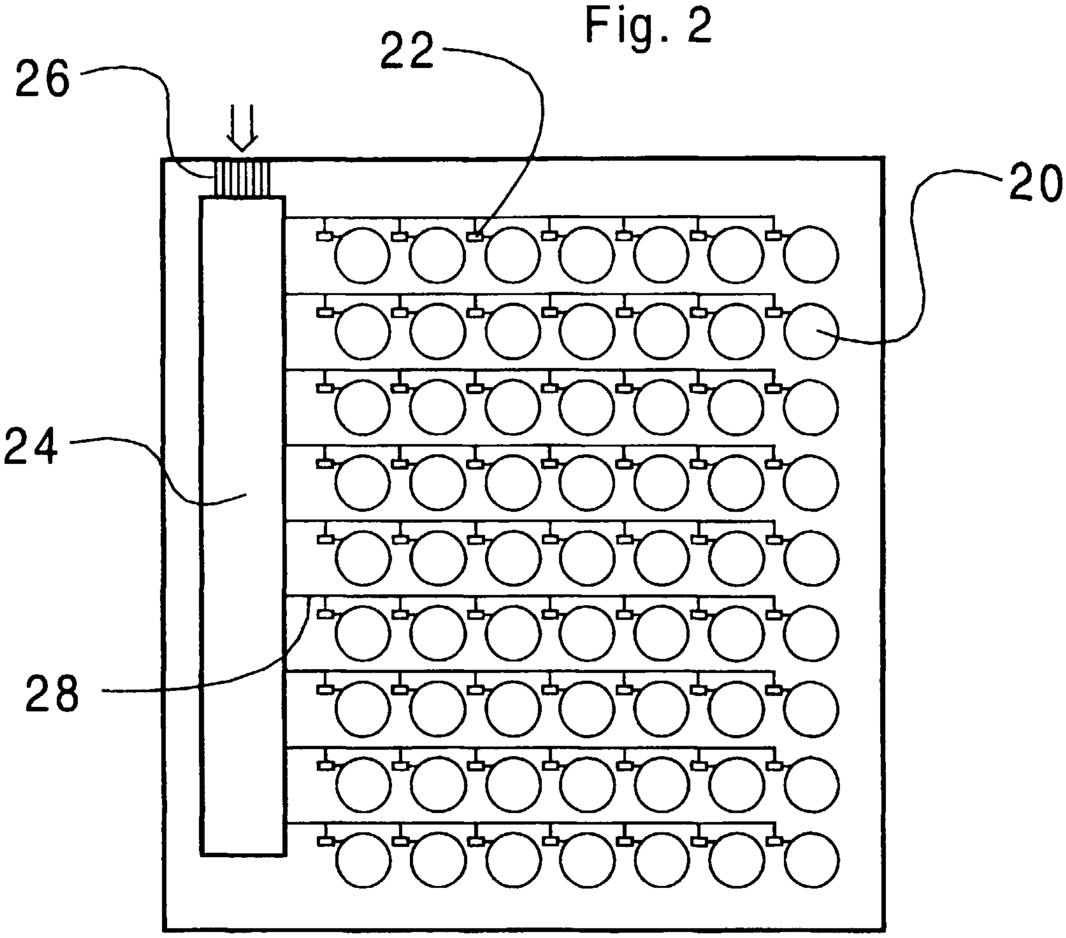


Fig. 3

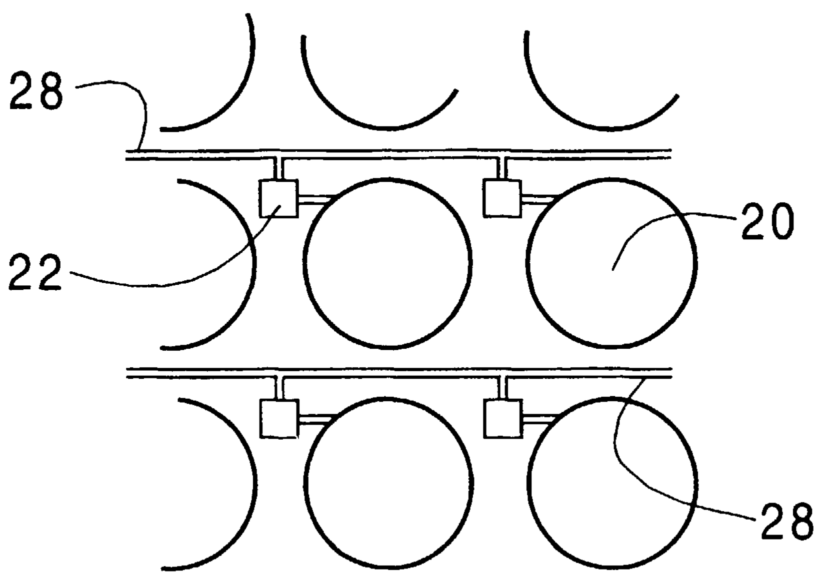


Fig. 4

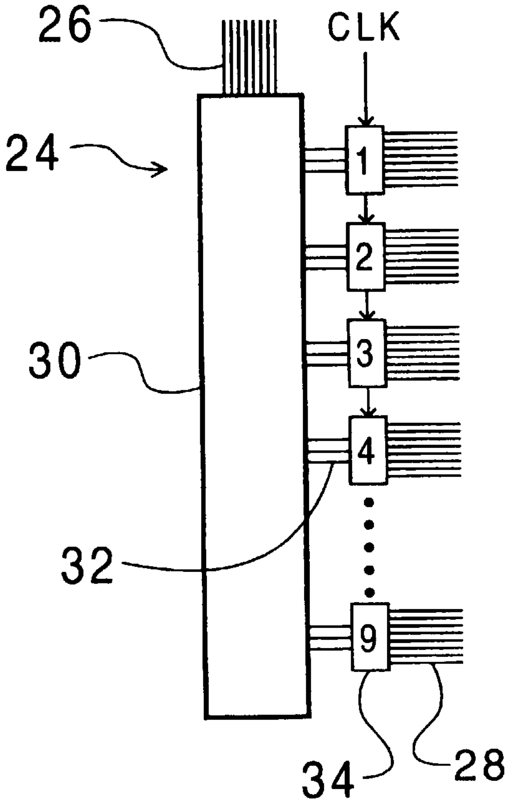
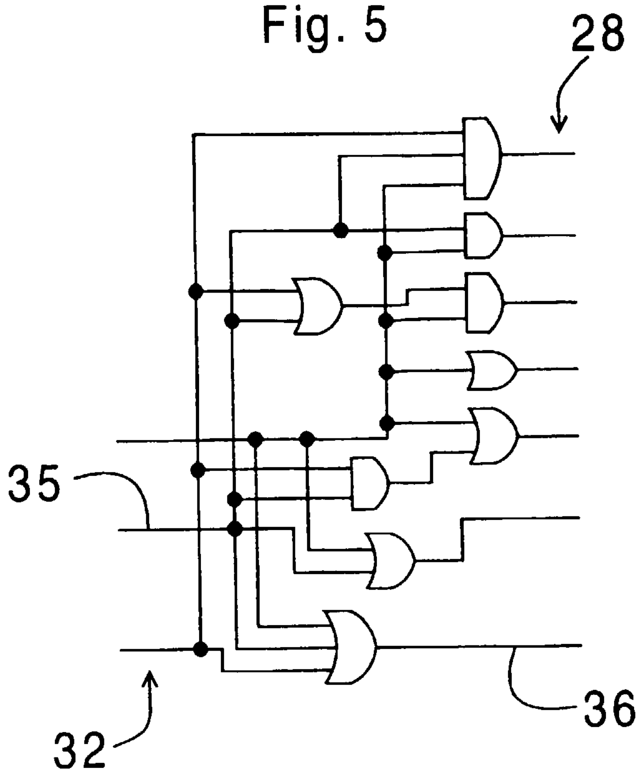


Fig. 5



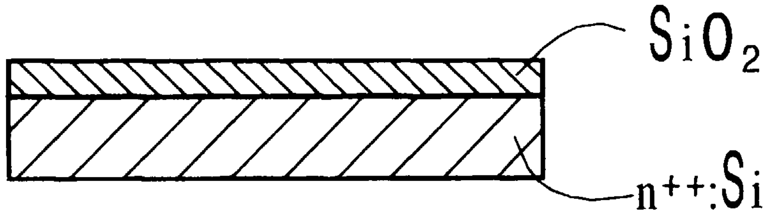


Fig. 6A

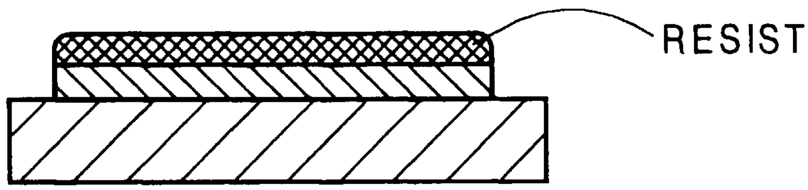


Fig. 6B

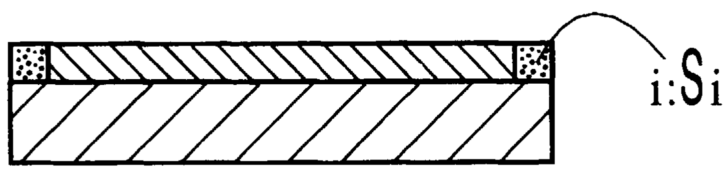


Fig. 6C

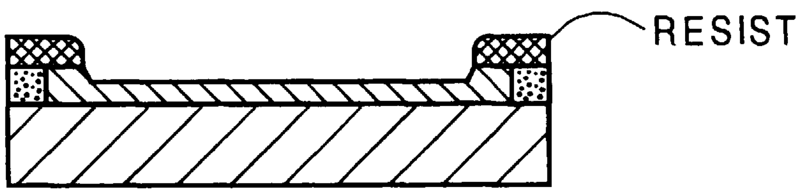


Fig. 6D

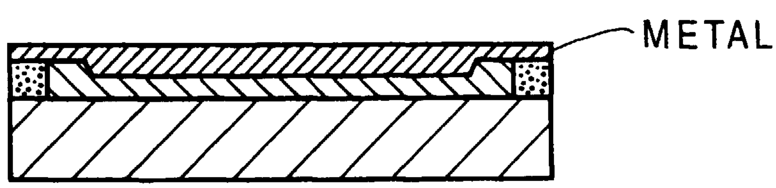


Fig. 6E

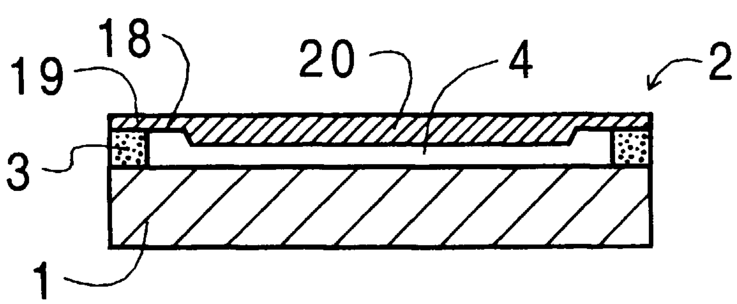


Fig. 6F

Fig. 7

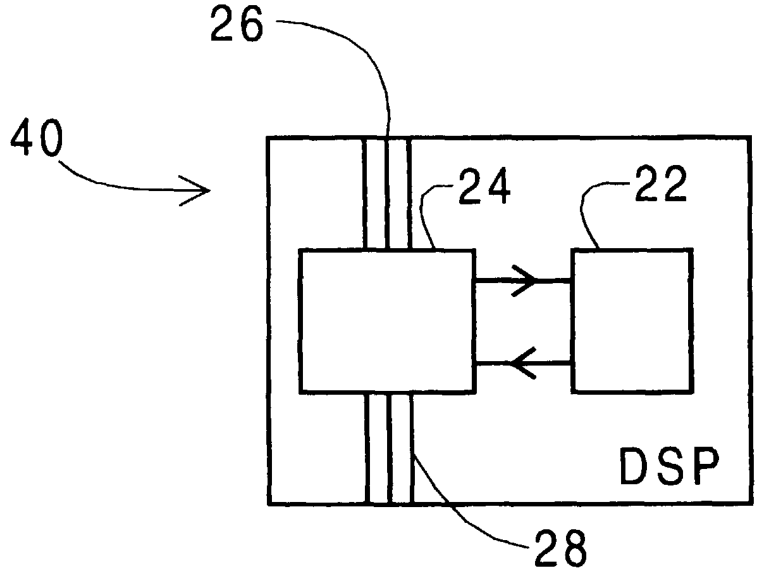


Fig. 8A

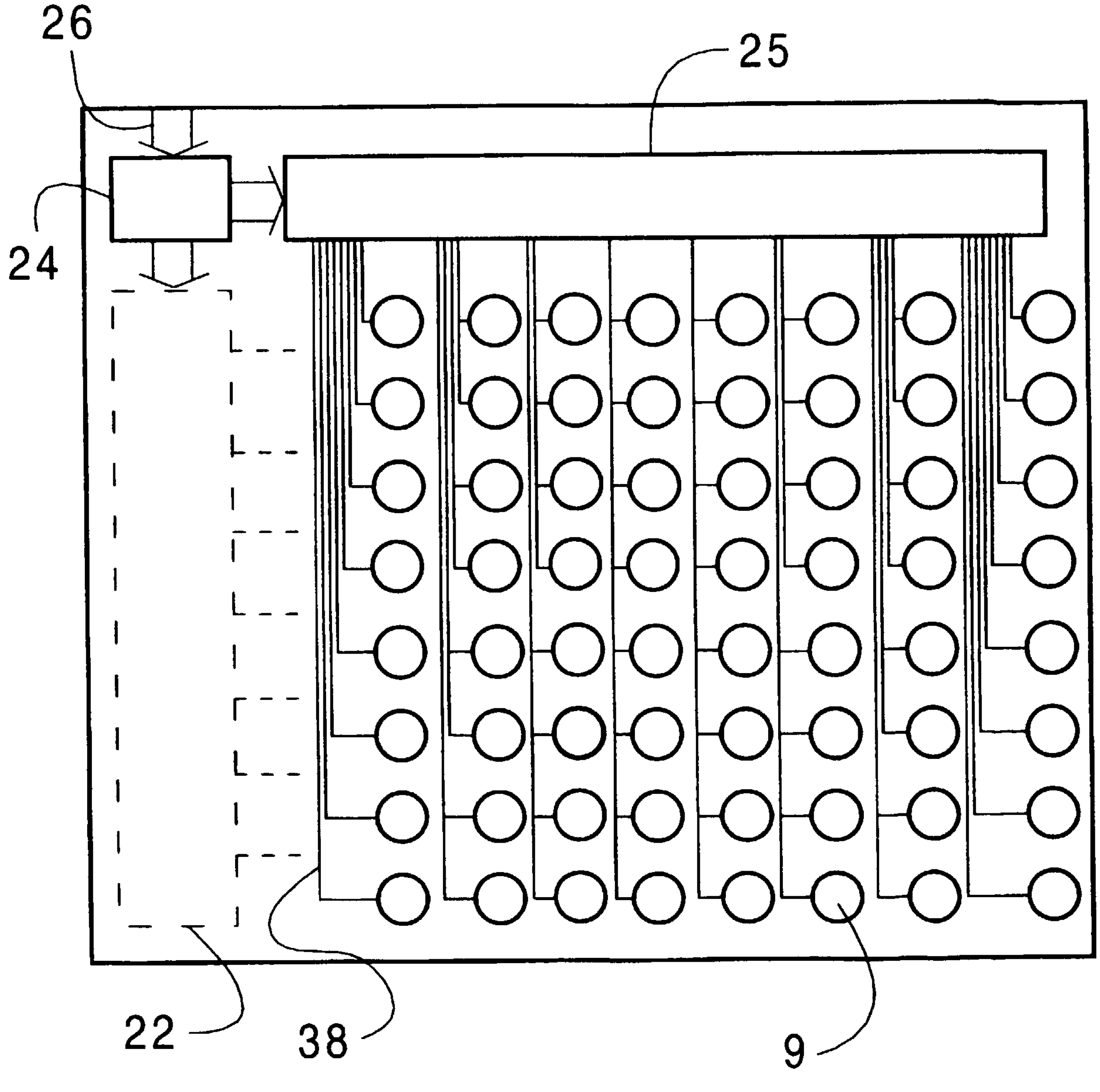
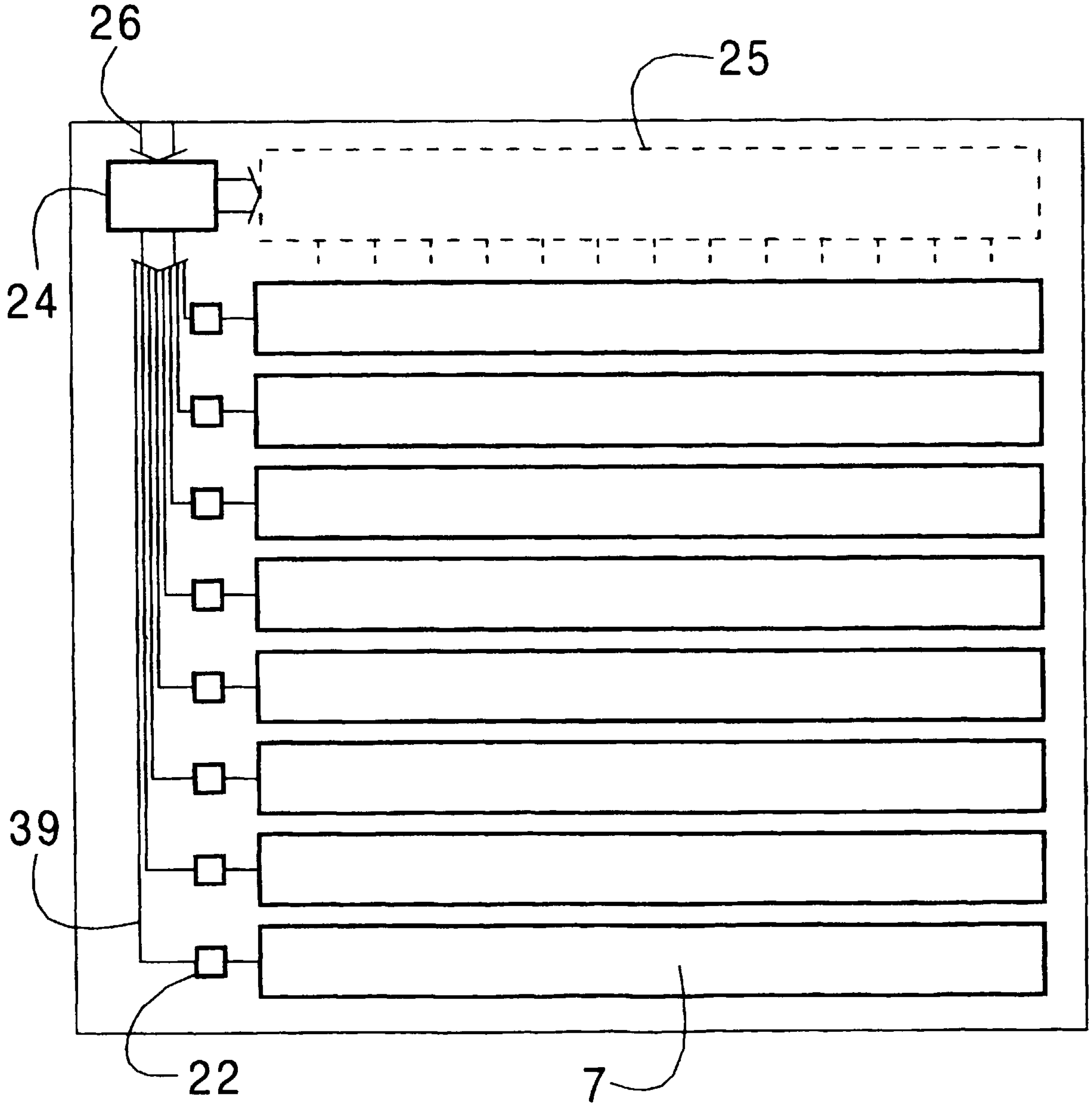


Fig. 8B



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EUROPEAN SEARCH REPORT

Application Number
EP 99 40 1288

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H04R

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	13 March 2000	Gastaldi, G

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