

Description

Background of the Invention

This invention relates to electroacoustic transducers, such as microphones, and in particular to a structure which is incorporated into a semiconductor substrate.

5 Demand is growing for electroacoustic transducers which may be formed as part of a semiconductor integrated circuit. These transducers may include, for example, microphones incorporated into the circuitry of telecommunications and audio recording equipment, hearing aid microphones and receivers, or miniature speakers. In the case of microphones, electrostatic device technology presently in widespread use generally takes the form of a metalized polymeric foil (which may be charged) supported
10 over a metalized backplate or stationary structure so as to form a variable capacitor responsive to voiceband frequencies. While adequate, such devices are relatively large, discrete components which cannot be integrated into the semiconductor integrated circuitry with which they are used.

Previous designs of integrated transducers propose to make the transducer diaphragm by thinning a portion of the semiconductor substrate. The diaphragm then has a considerable stiffness which is
15 demonstrated by tensile stress resulting from a heavy boron impurity concentration.

A capacitive pressure transducer using this type of diaphragm is known from EP-A-49 344. The diaphragm and the membrane, respectively, serve as the movable plate and the fixed plate of a capacitor, the capacitance of which varies in dependence on the pressure on opposite sides of the diaphragm. Such pressure transducers can be used as static pressure sensors but are not suitable as microphones owing
20 to the signal-to-noise ratio across the telephone frequency band.

In an integrated microphone it is desirable to make the area of the vibrating element as small as possible to reduce cost. However, a small area tends to cause a drop in sonic force on the diaphragm element, thereby lowering the sensitivity of the device. Further, smaller area diaphragms produce a smaller device capacitance which in turn tends to increase the noise associated with on-chip circuitry
25 coupled to the device and also tends to further decrease the integrated microphone sensitivity through capacitance divider action. In order to alleviate such effects of reduced area (i.e., reduced signal-to-noise ratio), it is desirable to reduce the stiffness of the diaphragm.

The above-noted effects of reduced diaphragm area may also be compensated for by a reduction in the thickness of the air gap between capacitor electrodes. We have found, however, that for air gaps
30 below approximately $1.5\text{ }\mu\text{m}$ with other dimensions optimized for certain telephone applications, the electrical output frequency response of a microphone with a tensioned diaphragm had a tendency to fall at an unacceptable rate with frequency when utilizing acoustic venting means, common in commercially available devices, comprising 4-20 holes around the periphery of the stationary electrode and backplate. That is, the devices would be overdamped, even at the critical 300-3 500 Hz portion of the audioband
35 which is transmitted in telephone equipment. Specifically, with an air gap of $0.25\text{ }\mu\text{m}$ which yielded the optimum signal-to-noise ratio, the response fell more than 20 dB across the telephone frequency band indicating severe overdamping. Sensitivity levels were also inoperably low. It is, therefore, also desirable to provide some acoustic venting means which will permit reduced area and produce an acceptable output signal at telephone band frequencies or other frequency bands of interest.

40 A reduction in the air gap thickness will also have another beneficial effect, which is to reduce the external dc voltage level needed to bias the diaphragm.

In addition, a silicon integrated microphone will generally have a nonrising output response as a function of frequency in the audio bandwidth. In some applications, it may be desirable to tailor the response to provide a peak at a certain frequency by means of an appropriately shaped acoustic port and
45 coupling cavity. Further, the microphone chip may, under certain circumstances, be subject to high electromagnetic interference (EMI), and so some shielding means may be needed. In the design of an integrated microphone, therefore, it is desirable to provide these functions with a minimum number of piece parts.

It is therefore an object of the invention to provide an integrated electroacoustic transducer with a
50 small diaphragm area which still provides an acceptable frequency response and signal-to-noise ratio. It is a further object of the invention to provide an electroacoustic transducer which can be operated at a low dc bias. It is a still further object of the invention to provide acoustical interconnection and tuning means, and EMI shielding means, for an integrated electroacoustic transducer.

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Summary of the Invention

These and other objects are achieved in accordance with the invention as set out in the claims.

Brief Description of the Drawing

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These and other features of the invention are delineated in detail in the following description. In the drawing :

Figure 1 is a cross-sectional view of a microphone in accordance with one embodiment of the invention ;

Figure 2 is a top view of a portion of the device illustrated in Fig. 1 ;

Figure 3 is an illustration based on computer modeling of typical frequency response curves predicted for microphones fabricated in accordance with the invention as compared with predictions of a prior art type device where the reference level is the 400 Hz response level of curve B ;

Figure 4 is a cross-sectional view of a microphone in accordance with a further embodiment of the invention ;

Figure 5 is a cross-sectional view of a microphone in accordance with a still further embodiment of the invention ; and

Figure 6 is a cross-sectional view of a microphone in accordance with a still further embodiment of the invention.

It will be appreciated that for purposes of illustration, these figures are not necessarily drawn to scale.

Detailed Description

Many of the basic features of the invention will be described with reference to the particular embodiment illustrated in Fig. 1. It will be appreciated that the Figure shows only a small portion of a semiconductor substrate which in this example includes a great many other identical, integrated, electronic transducer devices which are separated along saw lines, 40, following batch processing and testing.

The semiconductor substrate, 10, is a standard p-type silicon wafer having a thickness of approximately 300-600 μm (12-24 mils) and a $\langle 100 \rangle$ orientation. It will be appreciated that n-type wafers and other crystal orientations may be employed. A surface layer, 11, of p⁺ type is formed over at least portions of the substrate, for example, by an implantation of boron impurities to a depth of approximately 0.2 μm . The impurity concentration of this region is typically $5 \times 10^{19}/\text{cm}^3$.

Formed over the semiconductor substrate is a monocrystalline silicon epitaxial layer, 12. An appropriate area of the semiconductor substrate is etched to form a front acoustic cavity, 13, so that the portion, 14, of the epitaxial layer over the cavity forms the vibrating diaphragm element of the microphone. The characteristics of the diaphragm are discussed in more detail below.

Formed on the surface of the diaphragm is a metal layer, 15, such as Ti-Au, which comprises one electrode of a capacitor. This layer is typically 0.1-0.5 μm thick. Formed over the epitaxial layer is a spacer layer, 16, which is typically polycrystalline silicon and can be formed by chemical vapor deposition. The thickness of the layer in this example is 0.60 μm and will generally be in the range 0.1 μm -4.0 μm . A backplate layer, 17, is formed on the spacer layer with a portion (hereinafter the backplate) over the area of the diaphragm to establish an air gap, 18. The backplate may comprise a layer of SiO_2 , but could be any insulating layer or layers. The thickness of the layer is approximately 12 μm and will generally be in the range 6 μm -30 μm . A metal or other conducting layer, 19, is formed on the surface of the backplate facing the air gap and comprises the second electrode of the capacitor. It can be the same material and thickness as the first electrode, 15.

Formed through the backplate and electrode, 19, to the air gap is a continuous array of holes, 20, for acoustic venting. This feature will be discussed in more detail below.

The electronics for driving the device may be fabricated in the adjacent area of the semiconductor substrate designated 21, and electrical contact to the electrodes may be provided through via holes, 22 and 23. Contact to the outside may be provided through via holes, 23 and 24, and contact pads, 25 and 26, formed on the surface of the backplate layer. If desired, additional via holes (not shown) could be provided from the electronics to the outside to establish separate dc supply, signal and ground leads.

In operation, a dc bias is applied to electrodes, 15 and 19, and an acoustic signal is made incident on diaphragm, 14, through the front acoustic cavity. The signal causes the diaphragm to vibrate, thus varying the spacing between the electrodes and the capacitance of the capacitor. This change in capacitance can be detected as a change in voltage across some load element, integrated into area, 21, such as a second capacitance and parallel resistance (not shown), and an electrical equivalent to the acoustic signal is produced. The array of holes, 20, permits escape of air in the gap, 18, so that air stiffness in the gap is not a significant factor in the diaphragm motion. Desirably, the amplitude of the output signal as a function of frequency will be as shown in curve B in Fig. 3, where the signal (at constant sound pressure amplitude) is essentially flat or falls no more than 3 dB over the portion of the audioband transmitted in telephone applications (0.3-3.5 kHz). In accordance with a feature of the invention, the vibrating diaphragm is essentially nontensioned so that the stiffness of the diaphragm is dominated by the mechanical bending moment. This can be contrasted with previous designs for integrated microphones where the diaphragm was a thinned portion of the semiconductor substrate and had a stiffness which was dominated by tensile stress resulting from a heavy boron impurity concentration.

The advantage of using the nontensioned diaphragm results from the fact that the sensitivity (e) of the microphone depends upon the following parameters :

$$e\alpha \left[\frac{VA}{k_m + k_a} \right] / h_a \quad (1)$$

where V is the dc bias voltage across the electrodes, A is the area of the diaphragm, k_m is the effective mechanical lumped parameter (piston-like) stiffness of the diaphragm associated with the diaphragm's linearly averaged deflection, k_a is the stiffness of the rear acoustic cavity (shown, for example, in Fig. 4), and h_a is the distance between capacitor electrodes, linearly averaged over A, when the bias is applied to the electrodes. Thus, for the same sensitivity, the area, A, of the diaphragm may be reduced by decreasing the stiffness k_m of the diaphragm (k_a contributes less than 1/3 of the total stiffness acting on the diaphragm). We have found that when the stiffness is due primarily to tensile stress, a practical lower limit exists for reducing the membrane stiffness. In the present invention, however, k_m is significantly lowered in order that the diaphragm area may be reduced by allowing the mechanical bending moment of the diaphragm to be the dominant mechanical stiffness component. Further, when the stiffness is due to the mechanical bending moment, the thickness of the diaphragm can be significantly increased over a tensioned membrane and still produce a significantly lower stiffness and diaphragm area.

It will be appreciated that effective stiffness k_m , as used in this application, is the stiffness of a piston-like model where the deflection of the piston is equal to the diaphragm deflection averaged over the area of the diaphragm. For a nontensioned diaphragm, this stiffness is given approximately by the relationship:

$$k_m \approx \frac{192 \pi^2 D_p}{A} \quad (2)$$

where D_p is the flexural rigidity of the diaphragm.

In this example, the diaphragm thickness is 3.0 μm , the diaphragm is circular with a radius of 700 μm , k_m and k_a are approximately 625 and 175 N/m respectively. The biasing voltage across the electrodes is 1.3 volts. The resulting sensitivity is approximately -49 dB relative to 1 V/Pa at 400 Hz (excluding any signal voltage amplifiers that may be integrated on the chip microphone). For most nontensioned diaphragm applications, it is expected that the diaphragm thickness will range from 1 μm -5 μm , and area will range from 0.4 mm^2 -5 mm^2 to achieve proper sensitivity. Stiffness, k_m , of the nontensioned diaphragm is desirably less than 5 500 N/m.

While in this example the diaphragm was formed from a single crystal epitaxial layer, other types of nontensioned diaphragms might be employed. However, use of an epitaxial layer provides many advantages in terms of processing. For example, diaphragm thickness can be closely controlled by growing the layer over the boron-doped surface region, 11, and then utilizing an etchant which removes the semiconductor substrate but stops at the region, 11. The portion of region, 11, under the diaphragm can then be removed by applying an appropriate etchant such as KOH and H_2O for a predetermined period of time. As shown in Fig. 1, if desired, the etchant may be allowed to penetrate the epitaxial layer-substrate interface to achieve a desired diaphragm thickness less than the original epitaxial layer thickness. Close control of a nontensioned diaphragm's thickness, d, is important since $k_m \propto d^{-3}$. This step may also be desirable to remove boron impurities which may have diffused into the epitaxial layer from the substrate and added tension to the layer. A further advantage is the fact that the epitaxial layer can be anisotropically etched to provide via holes (22, 23, 24) or other useful features.

It will be appreciated that, in this example, the epitaxial layer is essentially free of impurities so that there is essentially no tension component contributing to the stiffness of the diaphragm. However, it is contemplated that layers may be fabricated with some tension component, as alluded to above, and still produce advantageous results. The invention is therefore directed to "essentially nontensioned" diaphragms which are intended to include those having a bending stiffness contributing at least 2/3 of the total stiffness of the diaphragm. It is further contemplated that impurities may be intentionally introduced into the epitaxial layer to satisfy certain needs. For example, the introduction of phosphorus impurities into the layer could provide compression in the layer to counteract any tension that might be produced by the presence of boron impurities.

The acoustic venting means comprises a continuous array of small holes, 20, extending through the backplate and electrode, 19, which array extends over essentially the entire area of the backplate and electrode portion co-extensive with the diaphragm. Such an array permits a narrow distance between electrodes, 15 and 19, without overdamping, thereby permitting a reduction in the applied dc bias and in the area of the diaphragm.

Fig. 2 is a top view of some of the holes in the array, which are greatly enlarged for illustrative purposes. It will be appreciated that essentially the entire area of the backplate is covered by these holes and consequently the array is considered to be continuous. The dynamic magnification factor, D, is defined in this application as the amount, in dB, that the frequency response rises in traversing the band from 400 Hz to the upper bound frequency of interest. For telephone applications where the upper bound frequency is 3 500 Hz, it is desirable that D be greater than -3.0 dB. Fig. 3 shows a generally desirable calculated, output characteristic (curve B) for telephony, which is achieved in this example in accordance with the invention. Returning to Fig. 2, such a characteristic can be achieved by a radius, r, of the holes

and a center-to-center spacing of the holes, 2ξ , which satisfies the relationship :

$$D = -10 \log \left[\left[1 - \left[\frac{\omega}{\omega_n} \right]^2 \right]^2 + 4 \left[\frac{\omega}{\omega_n} \frac{R_a}{R_c} \right]^2 \right] \quad (3)$$

where D is the minimum desirable magnification factor, ω is the highest acoustic input frequency which will be transmitted expressed in radians (here, $2\pi \times 3.5$ kHz), ω_n is the natural radian frequency of vibration of the diaphragm ($\sqrt{K/M}$), K is the combined stiffness, $k_m + k_a$, of the diaphragm and back acoustic cavity, M is the effective lumped parameter mass of the diaphragm compatible with the prior definition of k_m (which, for a nontensioned diaphragm is approximately 9/5 times the actual mass), R_c is the critical damping level ($2M\omega_n$), and R_a is the actual acoustic damping level of the air film in the air gap between electrodes. The acoustic damping is determined from the following :

$$R_a = \frac{NX^4 B 12 \pi \eta}{h_e^3} \quad (4)$$

where N is the number of holes, X is the local « radius-of-action » associated with each hole (i. e., the radius of the approximate circular area of air which will be vented through each hole (see Fig. 2), η is the coefficient of dynamic viscosity of air, and h_e was defined following equation (1). B is given by the equation :

$$B = \frac{1}{4} \left[1 + \ln \left(\frac{X}{r} \right)^2 \right] - \frac{3}{8} + \frac{1}{2} \left(\frac{r}{X} \right)^2 - \frac{1}{8} \left(\frac{r}{X} \right)^4 \quad (5)$$

It will be further appreciated that the geometry of the array yields the following relationships :

$$X = \lambda \xi \quad (6)$$

$$N = \frac{A}{\pi X^2} \quad (7)$$

$$\nu = 1 - \frac{N\pi r^2}{A} \quad (8)$$

where λ is determined by the hole configuration, A is the area of the backplate and electrode portion co-extensive with the diaphragm area, N is the total number of holes, and ν is the fraction of the backplate or electrode, 19, which is not consumed by the holes. For the pattern in this example, where the center of each hole lies at the corner of an equilateral triangle, $\lambda = 1.05$. For other patterns of holes, the backplate area (A) can easily be expressed as a unique function of ξ times N , thus determining X and λ from equations 6 and 7 above. For a square array of holes, for example, λ is 1.13. Also, if noncircular holes are used, the above relationships may still be used for first order calculations if the radius, r , is equated to

$$\sqrt{\frac{A_h}{\pi}}$$

where A_h is the area of the hole.

Thus, given the desired magnification factor D , the area, A , and mass of the diaphragm, M , the average distance between the electrodes when the bias is supplied, h_e , and the combined stiffness of the diaphragm and back acoustic cavity, K , the above equations can be solved to give combinations of hole radius and center-to-center spacing (r , 2ξ) or hole radius and number (r , N) which can be utilized for acoustic venting in accordance with the invention. The preferred combination is that which consumes the minimum amount of electrode area. (For a detailed discussion of the derivation of relationships governing acoustic impedance of the air gap in electrostatic transducers due to holes in one of the electrodes, see Skvor, « On the Acoustical Resistance due to Viscous Losses in the Air Gap of Electrostatic Transducers », *Acustica*, Vol. 19, pp. 259-299 (1967-68).

In this example, D is -0.8 dB, h_e is $0.56 \mu\text{m}$, N is approximately 2 000, r is $9.8 \mu\text{m}$ and 2ξ is $29.8 \mu\text{m}$ for a diaphragm with area of $1.54 \times 10^{-6} \text{ m}^2$, and effective mass of $1.93 \times 10^{-8} \text{ kgm}$. This leaves a total area not consumed by holes of 61 % (ν) of the backplate or electrode area. The capacitance is still sufficient, however, to produce a sufficiently high output signal as specified by the sensitivity previously given.

Of course, the above parameters may be varied according to specific needs. It is recommended, however, that there be a minimum of at least 50 holes per square millimeter to avoid overdamping in the output signal and that each hole have a diameter of less than $100 \mu\text{m}$ to allow sufficient diaphragm capacitance (at least 1 pF) for operation of the transducer. For the sake of comparison, curve A of Fig. 3 shows the calculated frequency response for a hypothetical microphone having the same dimensions as

described in the example shown by curve B, but not including the venting means of the invention. As compared with the microphone of curve B which includes 2 000 holes (1 300 holes/mm²) each having a diameter of 19.6 μ m, the microphone of curve A includes only 20 holes (13 holes/mm²) each having a diameter of 196 μ m. Both designs have the same electrode area not consumed by holes (61 %) so that the capacitances are equal and at least the potential signal-to-noise ratio is the same for both. Nevertheless, curve A shows a severely overdamped frequency response.

It should be appreciated that the average spacing between electrodes (h_e) when a bias is supplied should not vary too much from the air gap (h) with no bias applied if the system is to remain stable. It is recommended, therefore, that h_e be 4-10 % less than h . In this example, $h_e = 0.94 h$.

As noted previously, a reduced air gap, with is possible with the venting means of the invention, should also permit a reduction in the external dc bias needed for operation. For a gap, h , between electrodes of less than 3.0 μ m, it is expected that the microphone can be operated at less than 5 volts supplied to the capacitor electrodes.

It should be further appreciated that while the above relations allow one to specify a uniform air hole array (that is, a constant hole size and pattern), a somewhat nonuniform pattern that might possibly be desired may be designed by applying equation (4) piecewise across the backplate and electrode, and summing over N (holes).

The air gap, 18, electrode, 19, backplate layer, 17, and the air hole array, 20, may be conveniently formed by known deposition and photolithography steps. For example, layer 16, which may comprise polycrystalline silicon, can be deposited by chemical vapor deposition and the area which will comprise the air gap in then defined by selectively etching the layer. An etch-stop material, 27, such as BN or Si₃N₄, can be formed around the walls of the hole. The hole is then filled with a material such as polycrystalline silicon of SiO₂ and planarized. The electrode, 19, may then be formed by a selective deposition leaving the desired hole array therein. The backplate layer, 17, which may comprise BN or Si₃N₄, or a combination of like materials, is then deposited and the corresponding hole array formed therein by standard photolithography. The filler material can then be removed from the air cavity by applying another etchant through the hole array. Of course, during these various etching operations, the via holes, 22, 23 and 24, needed for interconnection can also be formed.

It will be appreciated that while the above example employed a circular diaphragm and backplate, the principles of the invention may be applied to any shaped diaphragm and backplate.

Various acoustical interconnection means and EMI shielding means may be incorporated into the basic microphone structure previously described. For example, Fig. 4 illustrates the formation of a back acoustic cavity, 30, adjacent to the air hole array, 20. This cavity is formed within a carrier substrate, 31, against which the silicon microphone structure is placed. This substrate can be a printed wiring board or other carrier substrate to which electronic components are usually attached.

Coupled to the front cavity, 13, is an acoustic port, 32, which is formed from an element, 33, which is typically a plastic closure. The acoustic port adds a degree-of-freedom to the microphone system and adds a peak to the frequency response of the device to serve various needs. Thus, in the present example, the response shown as curve C in Fig. 3, where the peak is placed near the upper end of the telephone band, is obtained from the microphone characterized by curve B simply by adding an acoustic port having a diameter of 150 μ m and a length of 1 600 μ m. In this example, the cavity, 13, has a volume of 0.94 mm³. Long holes with narrow diameters yielding high acoustic mass are generally needed in this silicon microphone application due to the large stiffness of the small, front acoustic cavity. In general, diameters of 100-180 μ m and lengths of 600-2 000 μ m are expected to be useful for producing peaks where desired. For telephone applications, it is desirable to form the peak within the frequency range 2.8-4.5 kHz. Although not illustrated in these figures, all members forming acoustic ports or cavities are acoustically sealed by standard means such as with adhesives or by clamping.

If shaping of the frequency response, as shown in curve C, is not needed, the embodiment shown in Fig. 5 might be utilized. Here, the cavity, 30, formed in carrier substrate, 31, acts as an extension of front cavity, 13, and the acoustic signal is made incident of the diaphragm through the hole array, 20. In this embodiment, in fact, the cavity extension, 30, may be eliminated so that the acoustic cavity is formed entirely within the semiconductor substrate. In any event, no extra parts are needed to form the acoustic interconnections. A further advantage is that electrical contact can be made to the microphone by wire bonds, 34 and 35, from the carrier substrate, 31, to the top of the backplate layer.

In the embodiment illustrated in Fig. 6, sound is again incident on the diaphragm through an acoustic port, 32, coupled to the front cavity, 13. Here, however, the sound port is formed in the carrier substrate, 31, so that the microphone is again mounted with the backplate side-up permitting wire bonding. Additionally, an enclosure member, 36, is provided surrounding the entire semiconductor microphone. This member can be made of conductive or conductively plated plastic or metal so as to provide a shield for the device against electromagnetic interference. At the same time, the member forms a back acoustic cavity, 30, for the microphone. The member can be grounded, for example, by bonding to grounded pad, 37, formed on the carrier substrate. Thus, EMI shielding is provided with a minimum of piece-parts.

It will be appreciated that the inventive features discussed herein could also apply to a pressure gradient type microphone where sound is allowed to strike both sides of the diaphragm, thus effecting a noise-canceling and directional response. To produce such a device in Figs. 4 and 5, a secondary sound

port would simply be placed in the carrier substrate, 31, while in the embodiment illustrated in Fig. 6 a small secondary port would be placed through enclosure member, 36. In any case, the second side of the diaphragm is accessed.

It will also be appreciated that although the above discussion has focused on a microphone, the principles of the invention may also be applicable to other types of electroacoustic transducers utilizing a capacitor whose capacitance varies in accordance with a vibrating diaphragm, whether an acoustic signal is converted to an electrical signal or vice-versa. For example, a loudspeaker or hearing aid receiver might be fabricated by applying a varying electrical signal to the capacitor electrodes (15 and 19) which causes vibration of the diaphragm (14) due to the varying deflection of the electrode (15) attached thereto. An acoustic output signal would therefore be produced. Thus, whichever way the energy conversion is taking place, the electric field between the electrodes varies in relationship with the vibrating diaphragm to permit conversion between electrical and acoustic signals.

It will also be realized that the invention is not limited to telephone band frequencies (0.3-3.5 kHz) but can be used in the full audio bandwidth (0.02-20 kHz). In fact, this silicon transducer invention can find application in the ultrasonic band (20-1 000 kHz).

Claims

1. A capacitive transducer device formed within a semiconductor substrate comprising a pair of electrodes, a diaphragm, and a perforated metallic membrane, respectively, connected to one of the electrodes, defining a cavity between the diaphragm and the membrane, characterized in that the diaphragm is an essentially non-tensioned diaphragm (14) which vibrates in response to an input signal at audio and/or ultrasonic frequencies, an essentially non-tensioned diaphragm being defined as a diaphragm in which at least 2/3 of the total stiffness is provided by the bending stiffness, and acoustic venting means (17, 19) comprising a continuous array of small holes (20) extending through one of the electrodes (19) to the cavity (18), the array covering essentially the entire area of that electrode which is co-extensive with the diaphragm (14), where the density of the holes in the array is at least 50 per square millimeter and the diameter of the holes is less than 100 microns.
2. The device according to claim 1, characterized in that the spacing between the electrodes (15, 19) is less than 3.0 microns when no dc bias is supplied to the electrodes.
3. The device according to claim 1, characterized in that the area of the diaphragm (14) is less than 8 mm².
4. The device according to claim 1, characterized in that the transducer is adapted to operate with a dc bias across the electrodes of less than 5 volts.
5. The device according to claim 1, characterized in that the dynamic magnification factor of the output response of the transducer is greater than or equal to -3.0 dB.
6. The device according to claim 1, characterized in that the radius, r, center-to-center spacing, 2 ξ and number, N, of holes in the array satisfies the relationships:

$$D = -10 \log \left[\left[1 - \left[\frac{\omega}{\omega_n} \right]^2 \right]^2 + 4 \left[\frac{\omega}{\omega_n} \frac{R_a}{R_c} \right]^2 \right]$$

$$R_a = \frac{NX^4 B 12 \pi \eta}{h_a^3}$$

$$B = \frac{1}{4} \left[\ln \left(\frac{X}{r} \right)^2 \right] - \frac{3}{8} - \frac{1}{2} \left(\frac{r}{X} \right)^2 - \frac{1}{8} \left(\frac{r}{X} \right)^4$$

$$X = \lambda \xi \quad \text{and}$$

$$N = \frac{A}{\pi X^2}$$

where D is the minimum desirable dynamic magnification factor, ω is the highest radian frequency of the input signal to be transmitted, ω_n is the natural radian frequency of vibration of the diaphragm, R_a is the damping level of the air in the gap, R_c is the critical damping level, X is the local radius-of-action associated with each hole, h_a is the average distance between the electrodes when the desired dc bias is supplied thereto, λ is a factor relating X and ξ for the geometry of the hole array, A is the area of diaphragm, and η is the coefficient of dynamic viscosity of air.

7. The device according to claim 1, characterized in that the diaphragm (14) is a single crystalline epitaxial layer (12) formed over the surface of a semiconductor substrate (10).

port would simply be placed in the carrier substrate, 31, while in the embodiment illustrated in Fig. 6 a small secondary port would be placed through enclosure member, 36. In any case, the second side of the diaphragm is accessed.

It will also be appreciated that although the above discussion has focused on a microphone, the principles of the invention may also be applicable to other types of electroacoustic transducers utilizing a capacitor whose capacitance varies in accordance with a vibrating diaphragm, whether an acoustic signal is converted to an electrical signal or vice-versa. For example, a loudspeaker or hearing aid receiver might be fabricated by applying a varying electrical signal to the capacitor electrodes (15 and 19) which causes vibration of the diaphragm (14) due to the varying deflection of the electrode (15) attached thereto. An acoustic output signal would therefore be produced. Thus, whichever way the energy conversion is taking place, the electric field between the electrodes varies in relationship with the vibrating diaphragm to permit conversion between electrical and acoustic signals.

It will also be realized that the invention is not limited to telephone band frequencies (0.3-3.5 kHz) but can be used in the full audio bandwidth (0.02-20 kHz). In fact, this silicon transducer invention can find application in the ultrasonic band (20-1 000 kHz).

Claims

1. A capacitive transducer device formed within a semiconductor substrate comprising a pair of electrodes, a diaphragm, and a perforated metallic membrane, respectively, connected to one of the electrodes, defining a cavity between the diaphragm and the membrane, characterized in that the diaphragm is an essentially non-tensioned diaphragm (14) which vibrates in response to an input signal at audio and/or ultrasonic frequencies, an essentially non-tensioned diaphragm being defined as a diaphragm in which at least 2/3 of the total stiffness is provided by the bending stiffness, and acoustic venting means (17, 19) comprising a continuous array of small holes (20) extending through one of the electrodes (19) to the cavity (18), the array covering essentially the entire area of that electrode which is co-extensive with the diaphragm (14), where the density of the holes in the array is at least 50 per square millimeter and the diameter of the holes is less than 100 microns.

2. The device according to claim 1, characterized in that the spacing between the electrodes (15, 19) is less than 3.0 microns when no dc bias is supplied to the electrodes.

3. The device according to claim 1, characterized in that the area of the diaphragm (14) is less than 8 mm².

4. The device according to claim 1, characterized in that the transducer is adapted to operate with a dc bias across the electrodes of less than 5 volts.

5. The device according to claim 1, characterized in that the dynamic magnification factor of the output response of the transducer is greater than or equal to -3.0 dB.

6. The device according to claim 1, characterized in that the radius, r , center-to-center spacing, 2ξ and number, N , of holes in the array satisfies the relationships:

$$D = -10 \log \left[\left[1 - \left[\frac{\omega}{\omega_n} \right]^2 \right]^2 + 4 \left[\frac{\omega}{\omega_n} \frac{R_a}{R_c} \right]^2 \right]$$

$$R_a = \frac{NX^4 B 12 \pi \eta}{h_e^3}$$

$$B = \frac{1}{4} \left[\ln \left(\frac{X}{r} \right)^2 \right] - \frac{3}{8} + \frac{1}{2} \left(\frac{r}{X} \right)^2 - \frac{1}{8} \left(\frac{r}{X} \right)^4$$

$$X = \lambda \xi \quad \text{and}$$

$$N = \frac{A}{\pi X^2}$$

where D is the minimum desirable dynamic magnification factor, ω is the highest radian frequency of the input signal to be transmitted, ω_n is the natural radian frequency of vibration of the diaphragm, R_a is the damping level of the air in the gap, R_c is the critical damping level, X is the local radius-of-action associated with each hole, h_e is the average distance between the electrodes when the desired dc bias is supplied thereto, λ is a factor relating X and ξ for the geometry of the hole array, A is the area of diaphragm, and η is the coefficient of dynamic viscosity of air.

7. The device according to claim 1, characterized in that the diaphragm (14) is a single crystalline epitaxial layer (12) formed over the surface of a semiconductor substrate (10).



8. The device according to claim 7, characterized in that the thickness of the epitaxial layer (12) is in the range 1-5 microns.

9. The device according to any of the claims 1-8, characterized in that the total effective lumped parameter stiffness of the diaphragm due to mechanical bending moment and tension, associated with a linearly average deflection, is less than 5 500 N/m.

10. The device according to claim 7, characterized in that the epitaxial layer (12) is formed over a surface layer (11) in the substrate which has a higher impurity concentration than the bulk of the substrate.

11. The device according to any of claims 1-10, characterized in that the device further comprises : a front acoustic cavity (13) defined by a portion of the semiconductor substrate adjacent to the diaphragm and a rear acoustic cavity (30) adjacent to one of the electrodes and defined by a member (36) which also shields the transducer from electromagnetic interference.

15 Patentansprüche

1. Kapazitiver Wandler, der innerhalb eines Halbleitersubstrats gebildet ist, mit einem Elektrodenpaar, einer Membran und einer perforierten metallischen Blende, die je mit einer der Elektroden verbunden sind, welche einen Hohlraum zwischen der Membran und der Blende definieren, dadurch gekennzeichnet, daß die Membran eine im wesentlichen nicht gespannte Membran (14) ist, die abhängig von einem Eingangssignal bei Ton- und/oder Ultraschallfrequenzen schwingt, wobei eine im wesentlichen nicht gespannte Membran als eine Membran definiert ist, bei der wenigstens 2/3 der Gesamtsteifigkeit durch die Biegesteifigkeit geliefert wird, daß eine akkustische Druckausgleichseinrichtung (17, 19) vorgesehen ist, die eine kontinuierliche Anordnung kleiner, durch eine der Elektroden (19) in den Hohlraum (18) führende Löcher (20) aufweist und die Anordnung im wesentlichen die gesamte Fläche derjenigen Elektrode überdeckt, welche sich parallel zu der Membran (14) erstreckt, und daß die Dichte der Löcher in der Anordnung wenigstens 50 pro Quadratmillimeter beträgt und der Durchmesser der Löcher kleiner als 100 Mikrometer ist.

2. Wandler nach Anspruch 1, dadurch gekennzeichnet, daß der Abstand zwischen den Elektroden (15, 19) kleiner als 3,0 Mikrometer beträgt, wenn keine Gleichvorspannung an die Elektroden angelegt ist.

3. Wandler nach Anspruch 1, dadurch gekennzeichnet, daß die Fläche der Membran (14) kleiner als 8 mm² beträgt.

4. Wandler nach Anspruch 1, dadurch gekennzeichnet, daß er mit einer Gleichvorspannung zwischen den Elektroden von weniger als 5 V arbeiten kann.

5. Wandler nach Anspruch 1, dadurch gekennzeichnet, daß der dynamische Überhöhungsfaktor der Ausgangskurve des Wandlers größer als oder gleich -3,0 dB ist.

6. Wandler nach Anspruch 1, dadurch gekennzeichnet, daß der Radius r, der Mittenabstand 2ξ und die Anzahl N der Löcher in der Anordnung den folgenden Beziehungen genügt :

$$D = -10 \log \left[\left[1 - \left[\frac{\omega}{\omega_n} \right]^2 \right]^2 + 4 \left[\frac{\omega}{\omega_n} \frac{R_a}{R_c} \right]^2 \right]$$

$$R_a = \frac{NX^4 B 12 \pi \eta}{h_e^3}$$

$$B = \frac{1}{4} \left[1n \left(\frac{X}{r} \right)^2 \right] - \frac{3}{8} + \frac{1}{2} \left(\frac{r}{X} \right)^2 - \frac{1}{8} \left(\frac{r}{X} \right)^4$$

$$X = \lambda \xi$$

und

$$N = \frac{A}{\pi X^2}$$

wobei D der minimal erwünschte dynamische Überhöhungsfaktor, ω die größte Kreisfrequenz des zu übertragenden Eingangssignals, ω_n die Kreisfrequenz der Eigenschwingung der Membran, R_a der Dämpfungswert der Luft im Spalt, R_c der kritische Dämpfungswert, X der lokale, jedem Loch zugeordnete Wirkungsradius, h_e der mittlere Abstand zwischen den Elektroden bei Anliegen der gewünschten Gleichvorspannung, λ ein X und ξ in Beziehung setzender Faktor für die Geometrie der Löcheranordnung, A die Fläche der Membran und η der Koeffizient der dynamischen Viskosität von Luft sind.

7. Wandler nach Anspruch 1, dadurch gekennzeichnet, daß die Membran (14) eine einkristalline epitaktische Schicht (12) ist, die auf der Oberfläche eines Halbleitersubstrats (10) gebildet ist.

8. Wandler nach Anspruch 7, dadurch gekennzeichnet, daß die Dicke der epitaktischen Schicht (12) im Bereich von 1 bis 5 Mikrometer liegt.



9. Wandler nach einem der Ansprüche 1 bis 8, dadurch gekennzeichnet, daß die gesamt wirksame, für konzentrierte Parameter geltende Steifigkeit der Membran aufgrund eines mechanischen Biegemoments und mechanischer Spannung bei linearer mittlerer Ablenkung weniger als 5 500 N/m beträgt.

10. Wandler nach Anspruch 7, dadurch gekennzeichnet, daß die epitaktische Schicht (12) auf einer Oberflächenschicht (11) im Substrat gebildet ist, die eine höhere Dotierungskonzentration als das Gesamtmaterial des Substrats hat.

11. Wandler nach einem der Ansprüche 1 bis 10, dadurch gekennzeichnet, daß der Wandler ferner aufweist : einen vorderen akustischen Hohlraum (13) der durch einen Teil des Halbleitersubstrats nahe der Membran gebildet wird, und einen hinteren akustischen Hohlraum (30) nahe einer der Elektroden, der durch ein Bauteil (36) gebildet wird, das außerdem den Wandler gegen elektromagnetische Störungen abschirmt.

Revendications

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1. Un dispositif transducteur capacitif formé dans un substrat semiconducteur, comprenant une paire d'électrodes, une membrane et une lame métallique perforée respectivement connectées à l'une des électrodes, définissant une cavité entre la membrane et la lame, caractérisé en ce que la membrane est une membrane dans un état pratiquement sans tension (14) qui vibre sous l'effet d'un signal d'entrée à des fréquences audio et/ou ultrasonores, une membrane dans un état pratiquement sans tension étant définie comme une membrane dans laquelle deux tiers au moins de la raideur totale résultent de la raideur de flexion, et en ce qu'il existe des moyens de passage d'air de communication acoustique (17, 19) qui comprennent un réseau continu de petits trous (20) traversant l'une des électrodes (19) pour déboucher dans la cavité (18), ce réseau recouvrant pratiquement la totalité de l'étendue de cette électrode qui coïncide avec la membrane (14), et la densité des trous dans le réseau étant d'au moins 50 par millimètre carré, tandis que le diamètre des trous est inférieur à 100 micromètres.

2. Le dispositif selon la revendication 1, caractérisé en ce que l'écartement entre les électrodes (15, 19) est inférieur à 3,0 micromètres lorsque aucune polarisation continue n'est appliquée aux électrodes.

3. Le dispositif selon la revendication 1, caractérisé en ce que l'aire de la membrane (14) est inférieure à 8 mm².

4. Le dispositif selon la revendication 1, caractérisé en ce que le transducteur est conçu pour fonctionner avec une polarisation continue de moins de 5 volts entre les électrodes.

5. Le dispositif selon la revendication 1, caractérisé en ce que le facteur d'amplification dynamique de la réponse de sortie du transducteur est supérieur ou égal à -3,0 dB.

6. Le dispositif selon la revendication 1, caractérisé en ce que le rayon, r , l'écartement entre centres, 2ξ , et le nombre, N , de trous dans le réseau satisfont les relations :

$$D = -10 \log \left[\left[1 - \left[\frac{\omega}{\omega_n} \right]^2 \right]^2 + 4 \left[\frac{\omega}{\omega_n} \frac{R_a}{R_c} \right]^2 \right]$$

$$R_a = \frac{NX^4 B 12 \pi \eta}{h_e^3}$$

$$B = \frac{1}{4} \left[\ln \left(\frac{X}{r} \right) \right]^2 - \frac{3}{8} + \frac{1}{2} \left(\frac{r}{X} \right)^2 - \frac{1}{8} \left(\frac{r}{X} \right)^4$$

$$X = \lambda \xi$$

et

$$N = \frac{A}{\pi X^2}$$

dans lesquelles D est le facteur d'amplification dynamique minimale souhaitable, ω est la pulsation la plus élevée du signal d'entrée à transmettre, ω_n est la pulsation de vibration naturelle de la membrane, R_a est le niveau d'amortissement de l'air dans l'intervalle d'air, R_c est le niveau d'amortissement critique, X est le rayon d'action local associé à chaque trou, h_e est la distance moyenne entre les électrodes lorsque la polarisation continue désirée leur est appliquée, λ est un facteur liant X et ξ pour la configuration géométrique du réseau de trous, A est l'aire de la membrane et η est le coefficient de viscosité dynamique de l'air.

7. Le dispositif selon la revendication 1, caractérisé en ce que la membrane (14) consiste en une couche épitaxiale monocristalline (12) qui est formée sur la surface d'un substrat semiconducteur (10).

8. Le dispositif selon la revendication 7, caractérisé en ce que l'épaisseur de la couche épitaxiale (12) est dans la plage de 1-5 micromètres.



9. Le dispositif selon l'une quelconque des revendications 1-8, caractérisé en ce que la raideur effective totale de la membrane, exprimée par un paramètre localisé, qui est due au moment de flexion mécanique et à l'état de tension, associée à un déplacement considéré en moyenne linéaire, est inférieure à 5 500 N/m.

5 10. Le dispositif selon la revendication 7, caractérisé en ce que la couche épitaxiale (12) est formée sur une couche de surface (11) dans le substrat qui a une concentration en impuretés supérieure à celle du volume principal du substrat.

10 11. Le dispositif selon l'une quelconque des revendications 1-10, caractérisé en ce qu'il comprend en outre : une cavité acoustique avant (13) définie par une partie du substrat semiconducteur adjacente à la membrane ; et une cavité acoustique arrière (30) adjacente à l'une des électrodes, et définie par une pièce (36) qui blinde également le transducteur vis-à-vis de perturbations électromagnétiques.

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