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(54) INTEGRATED MULTIMODAL SENSOR DEVICE FOR INTRACRANIAL NEUROMONITORING

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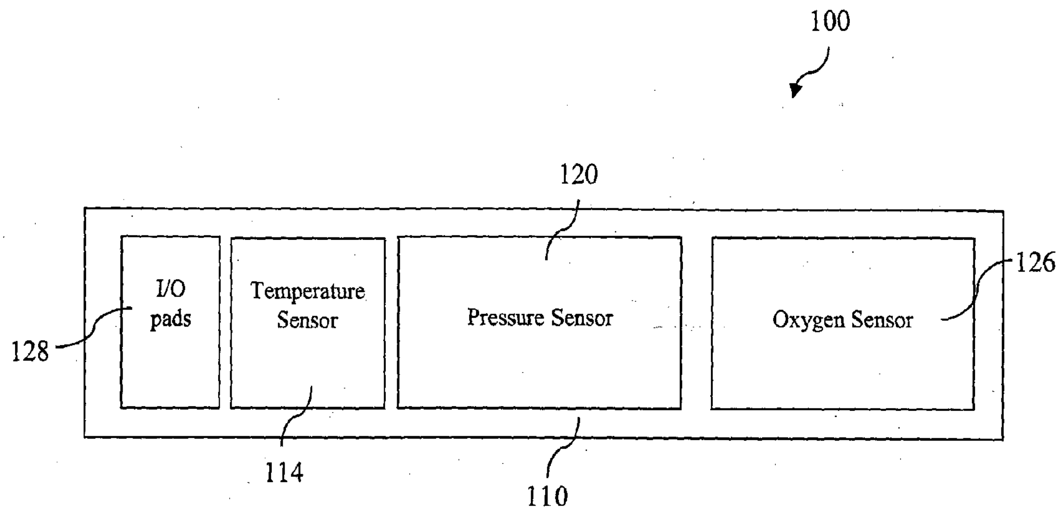
A61B 5/01	(2006.01)
A61B 5/03	(2006.01)

(52) **U.S. Cl.**

CPC ***A61B 5/6852*** (2013.01); ***A61B 5/01*** (2013.01); ***A61B 5/031*** (2013.01); ***A61B 5/14542*** (2013.01); ***A61B 5/14865*** (2013.01); ***A61B 5/0008*** (2013.01); *A61B 2562/063* (2013.01); *A61B 2562/0271* (2013.01); *A61B 2562/0247* (2013.01); *A61B 2562/028* (2013.01); *A61B 2562/125* (2013.01); *A61B 2562/164* (2013.01)

(57) **ABSTRACT**

There is provided a monolithically integrated multimodal sensor device for intracranial neuromonitoring, the sensor device including: a single substrate; a temperature sensor formed on a first portion of the single substrate for detecting temperature; a pressure sensor formed on a second portion of the single substrate for detecting intracranial pressure; and an oxygen sensor formed on a third portion of the single substrate for detecting oxygen concentration. In particular, sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device. There is also provided an integrated multimodal sensor system incorporating the sensor device and the associated methods of fabrication.



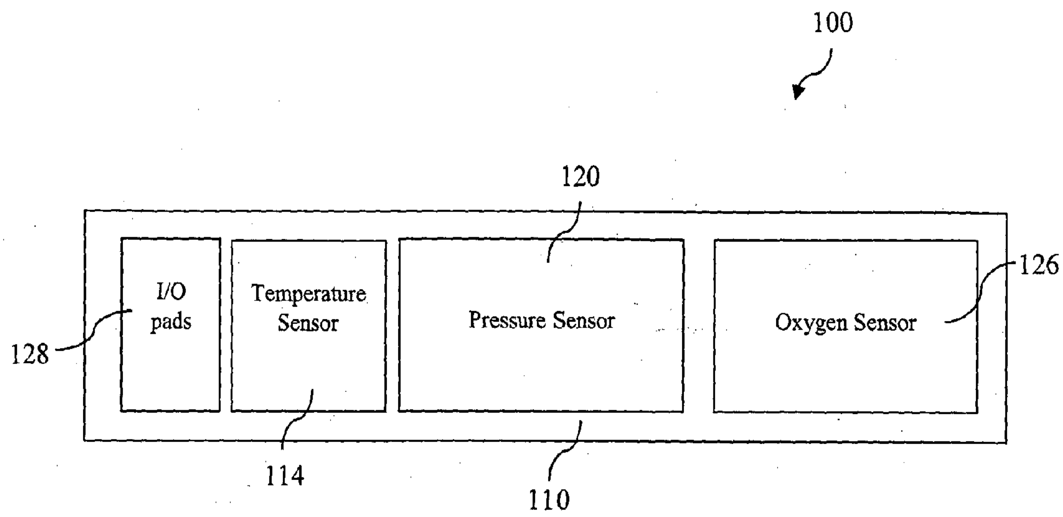

100
120
126
I/O
pads
Temperature
Sensor
Pressure Sensor
Oxygen Sensor
128
114
110

FIG. 1A

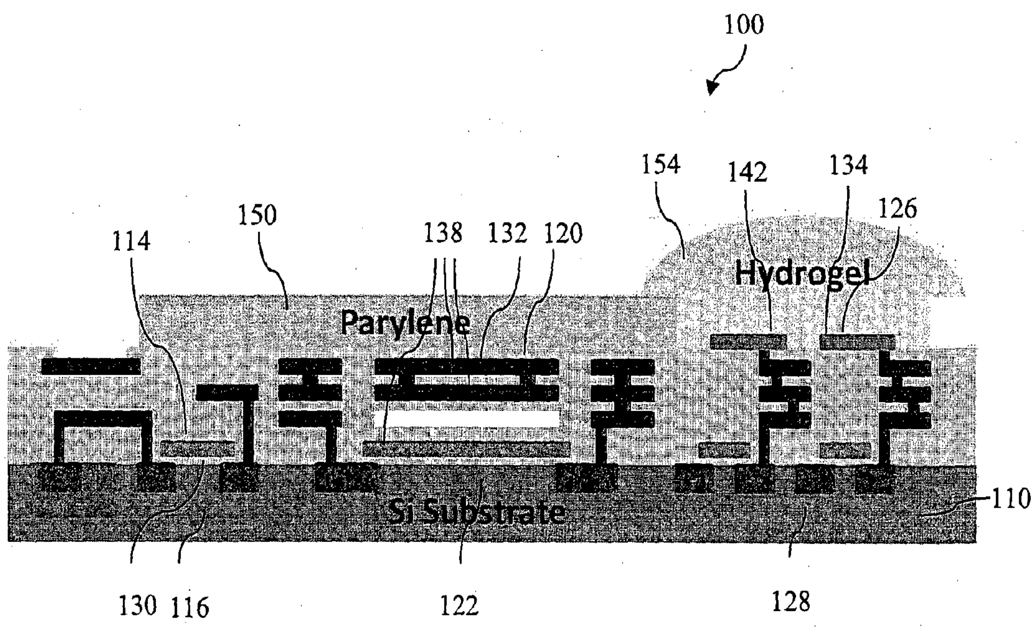

100
154
142
134
126
150
114
138
132
120
Hydrogel
Parylene
Si Substrate
110
130
116
122
128

FIG. 1B

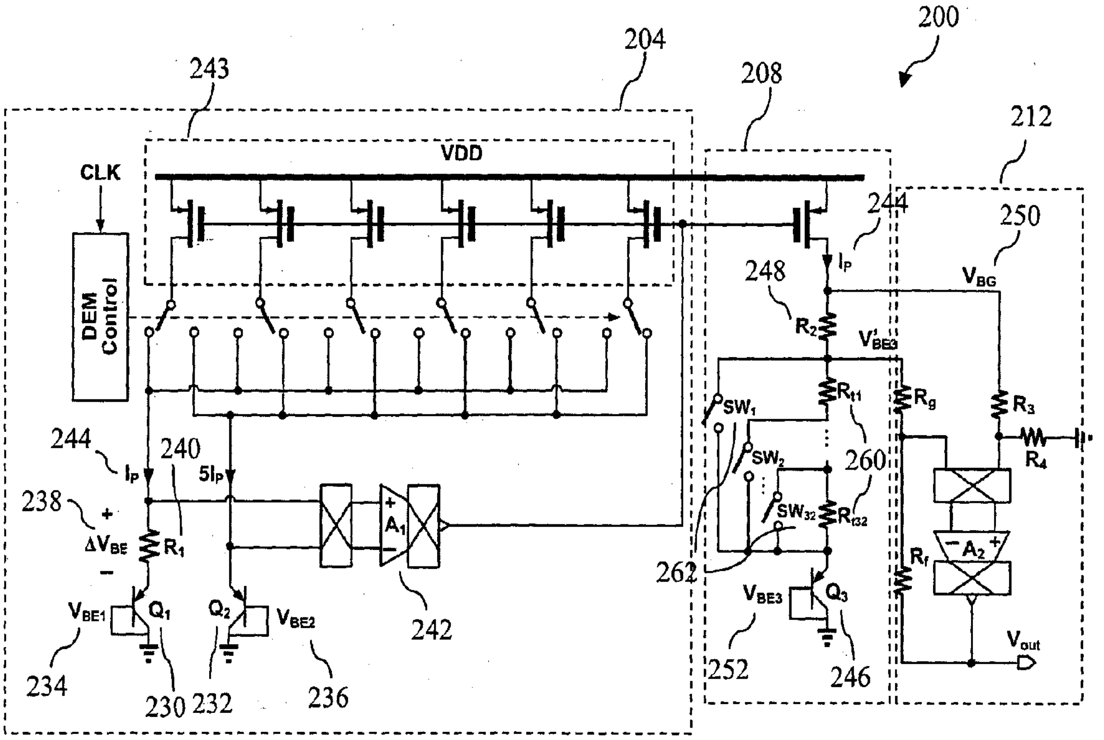

200
204
243
208
212
VDD
CLK
DEM Control
244
I_P
248
R_2
250
V_{BG}
V'_{BE3}
R_{t1}
R_g
R_3
R_4
SW_1
SW_2
SW_{32}
260
R_{t32}
R_f
A_2
262
V_{BE3}
Q_3
V_{out}
252
246
240
$5I_P$
238
ΔV_{BE}
R_1
A_1
V_{BE1}
Q_1
Q_2
V_{BE2}
242
234
230
232
236

FIG. 2

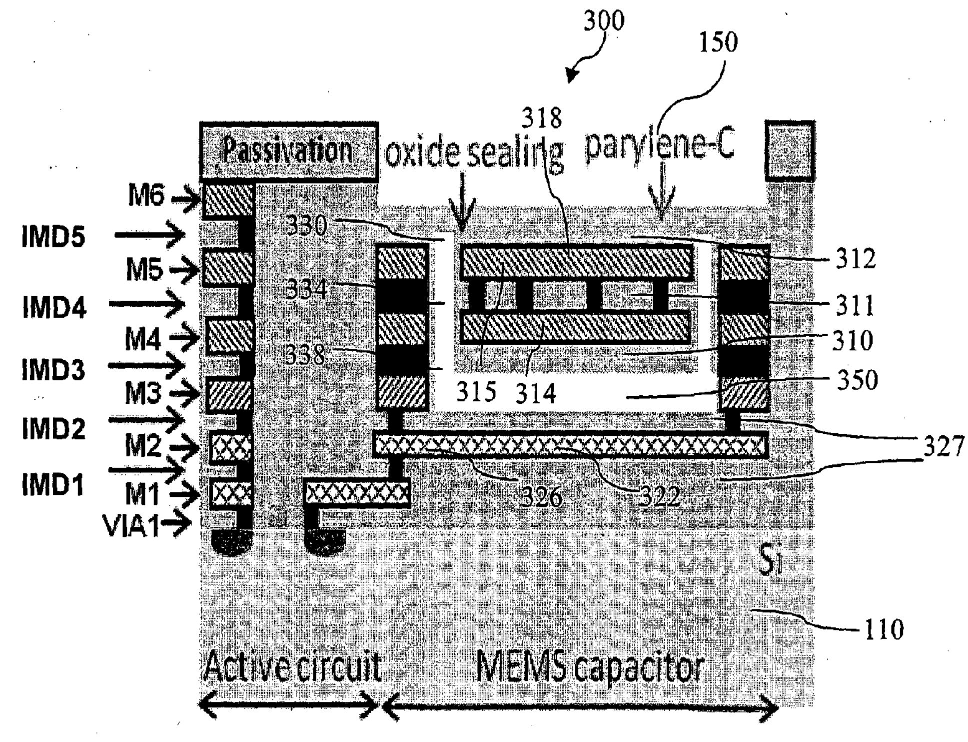

300
150
318
Passivation
oxide sealing
parylene-C
M6
IMD5
330
312
M5
334
311
IMD4
M4
338
310
IMD3
315
314
350
M3
IMD2
327
M2
IMD1
326
322
M1
VIA1
Si
110
Active circuit
MEMS capacitor

FIG. 3A

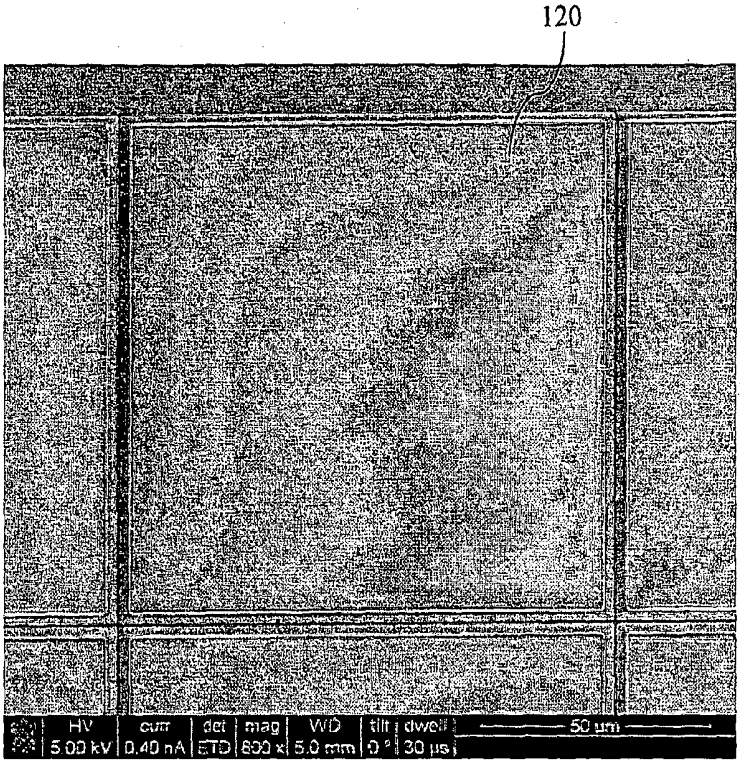

120
HV 5.00 kV
curr 0.40 nA
det ETD
mag 800 x
WD 5.0 mm
tilt 0 °
dwell 30 µs
50 µm

FIG. 3B

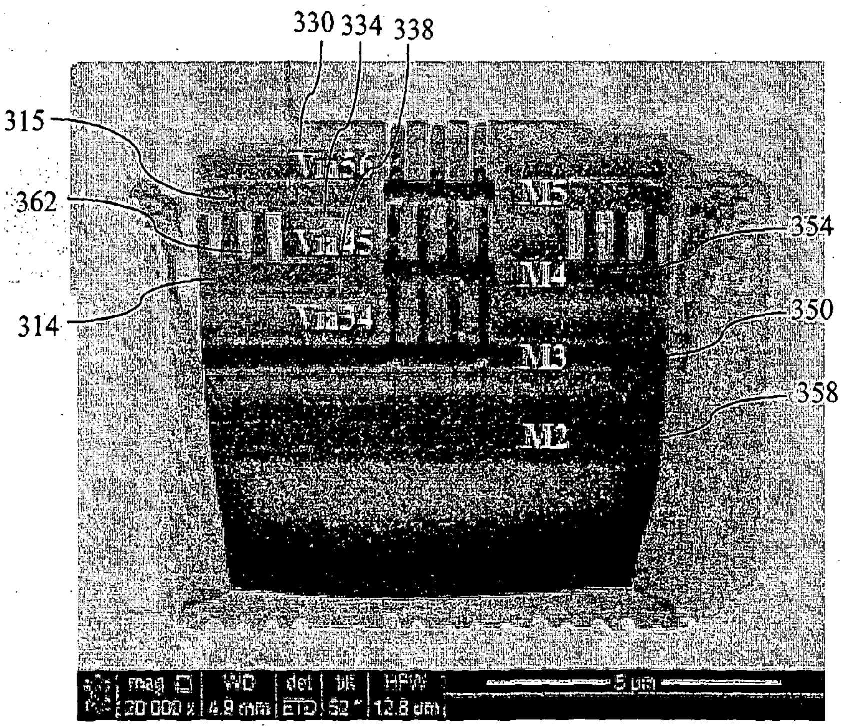

330
334
338
315
362
314
354
350
358
Via56
M5
Via45
M4
Via34
M3
M2
mag 20 000 x
WD 4.9 mm
det ETD
tilt 52 °
HFW 12.8 µm
5 µm

FIG. 3C

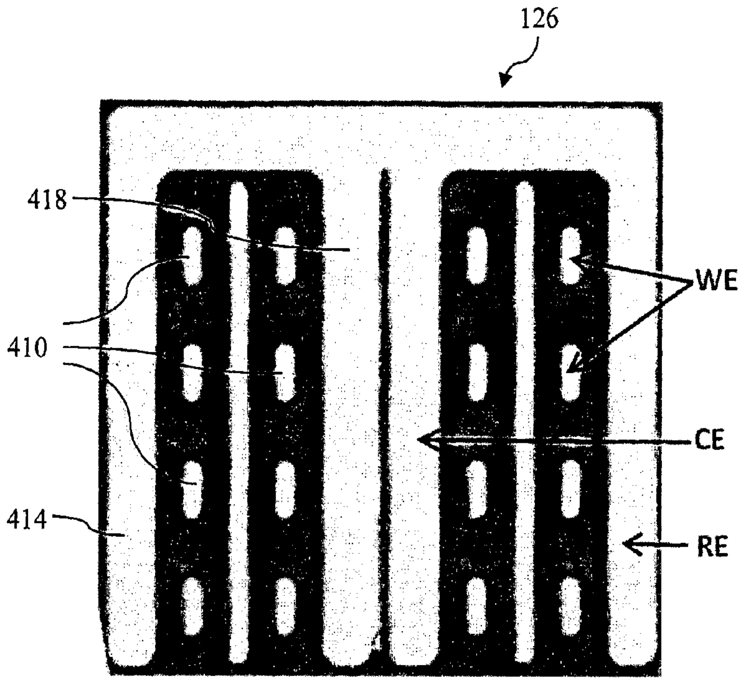

126
418
410
414
WE
CE
RE

FIG. 4

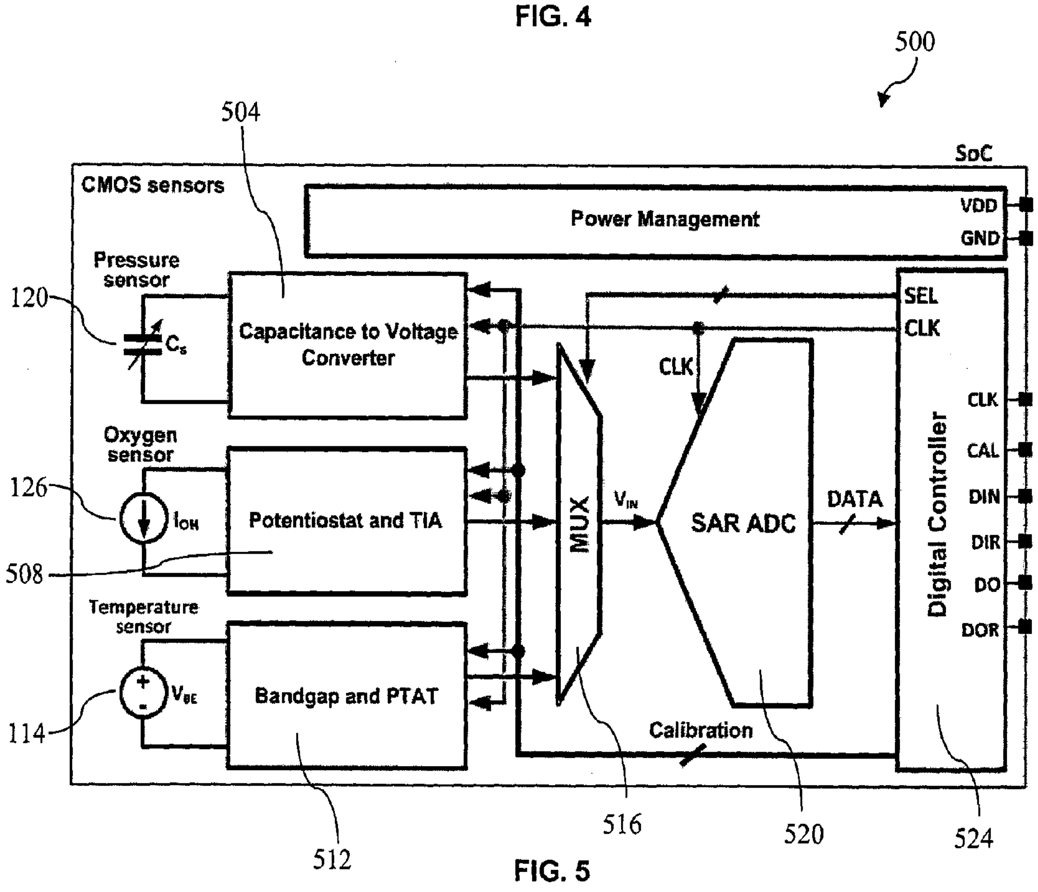

500
504
SoC
CMOS sensors
Power Management
VDD
GND
Pressure sensor
120
C_s
Capacitance to Voltage Converter
SEL
CLK
CLK
Oxygen sensor
126
I_{OH}
Potentiostat and TIA
508
MUX
V_{IN}
SAR ADC
DATA
Digital Controller
CLK
CAL
DIN
DIR
DO
DOR
Temperature sensor
114
V_{BE}
Bandgap and PTAT
Calibration
512
516
520
524

FIG. 5

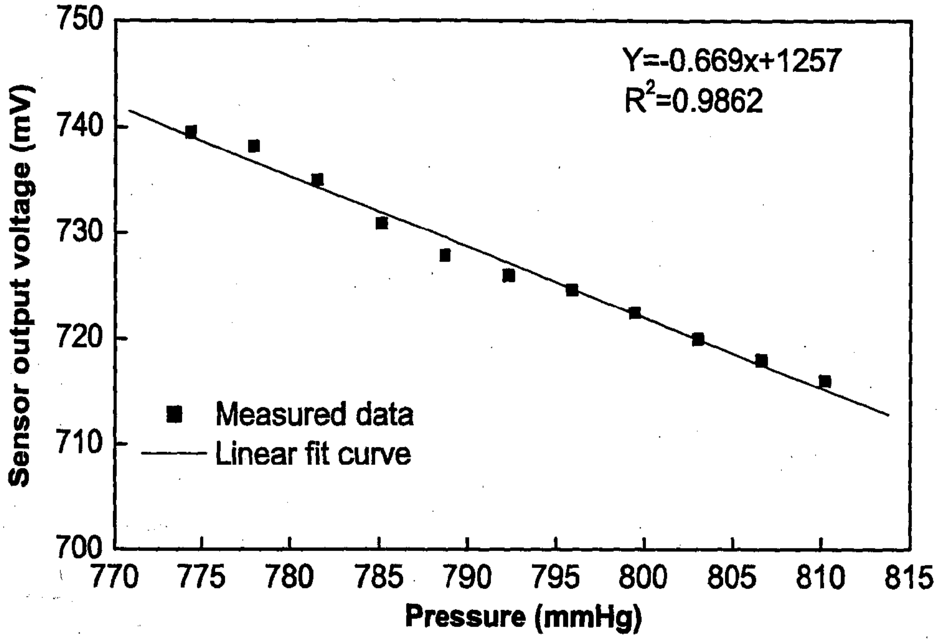

Y=-0.669x+1257
R²=0.9862
Measured data
Linear fit curve
Sensor output voltage (mV)
Pressure (mmHg)
750
740
730
720
710
700
770
775
780
785
790
795
800
805
810
815

FIG. 6A

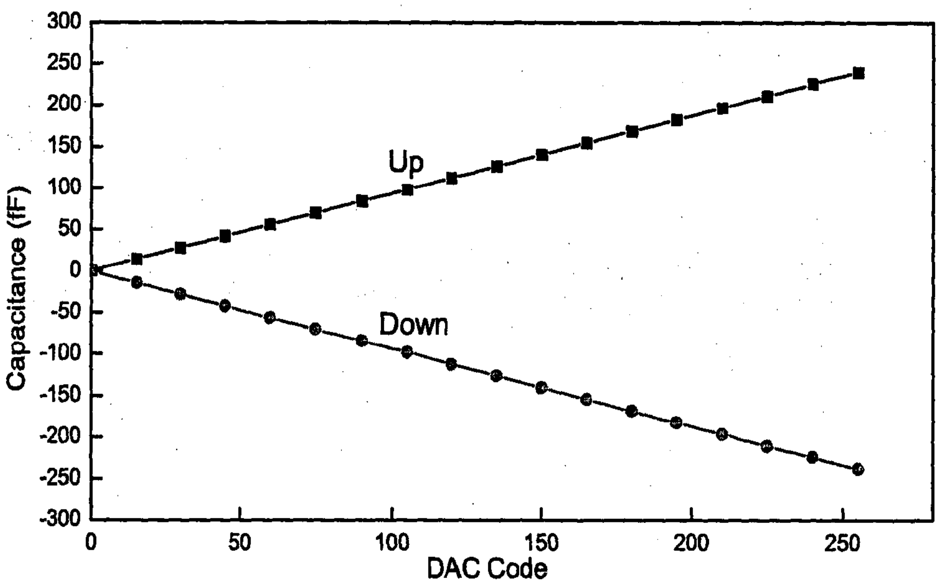

Up
Down
Capacitance (fF)
DAC Code
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
0
50
100
150
200
250

FIG. 6B

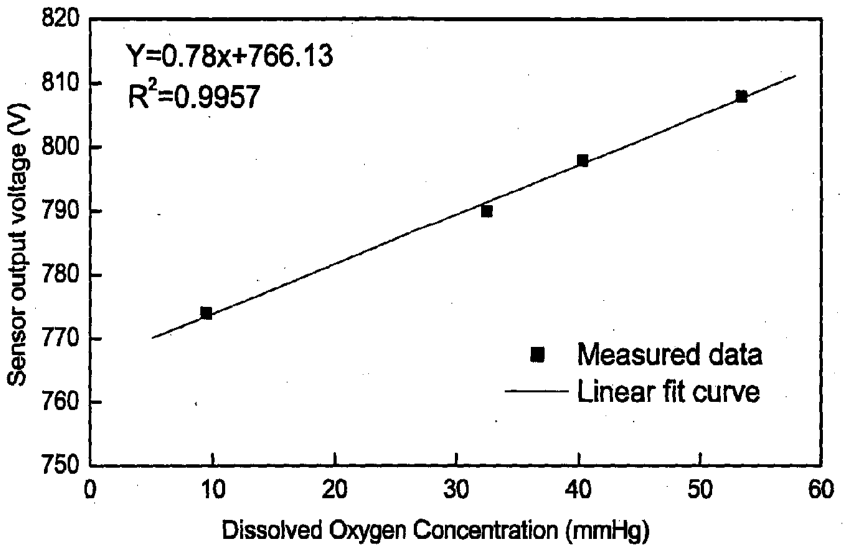

Y=0.78x+766.13
R^2=0.9957
Sensor output voltage (V)
820
810
800
790
780
770
760
750
0
10
20
30
40
50
60
Dissolved Oxygen Concentration (mmHg)
Measured data
Linear fit curve

FIG. 7A

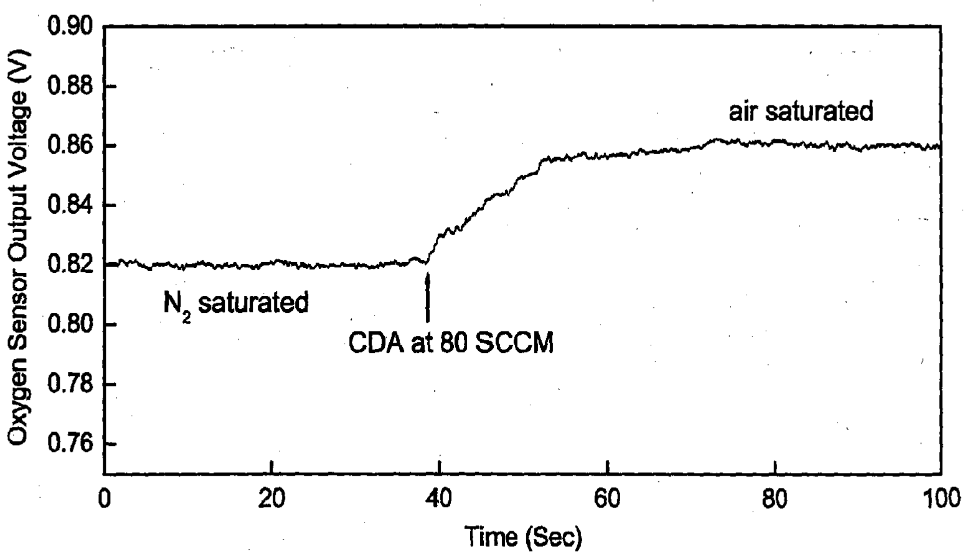

Oxygen Sensor Output Voltage (V)
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.76
air saturated
N_2 saturated
CDA at 80 SCCM
0
20
40
60
80
100
Time (Sec)

FIG. 7B

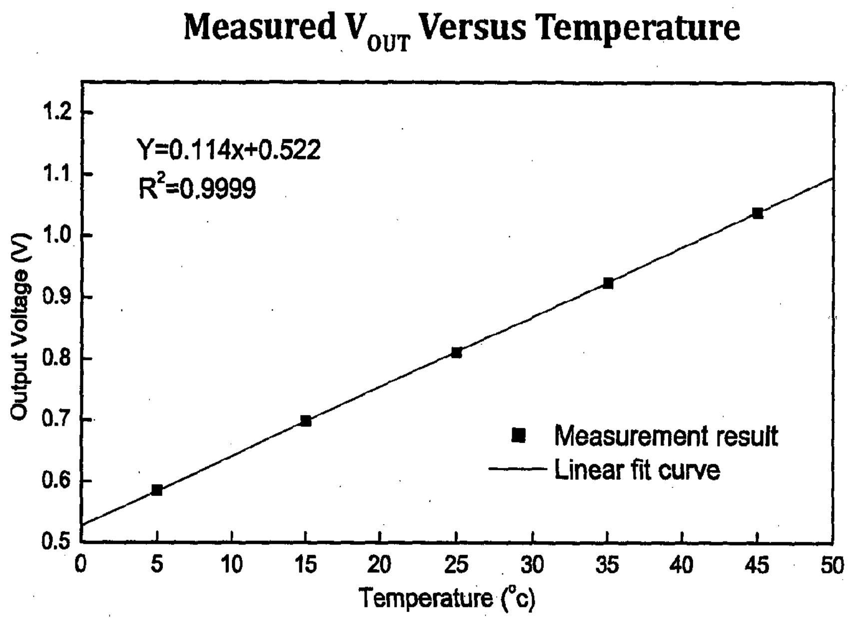

Measured V_{OUT} Versus Temperature
Y=0.114x+0.522
R^2=0.9999
Output Voltage (V)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
5
10
15
20
25
30
35
40
45
50
Temperature (°c)
Measurement result
Linear fit curve

FIG. 8A

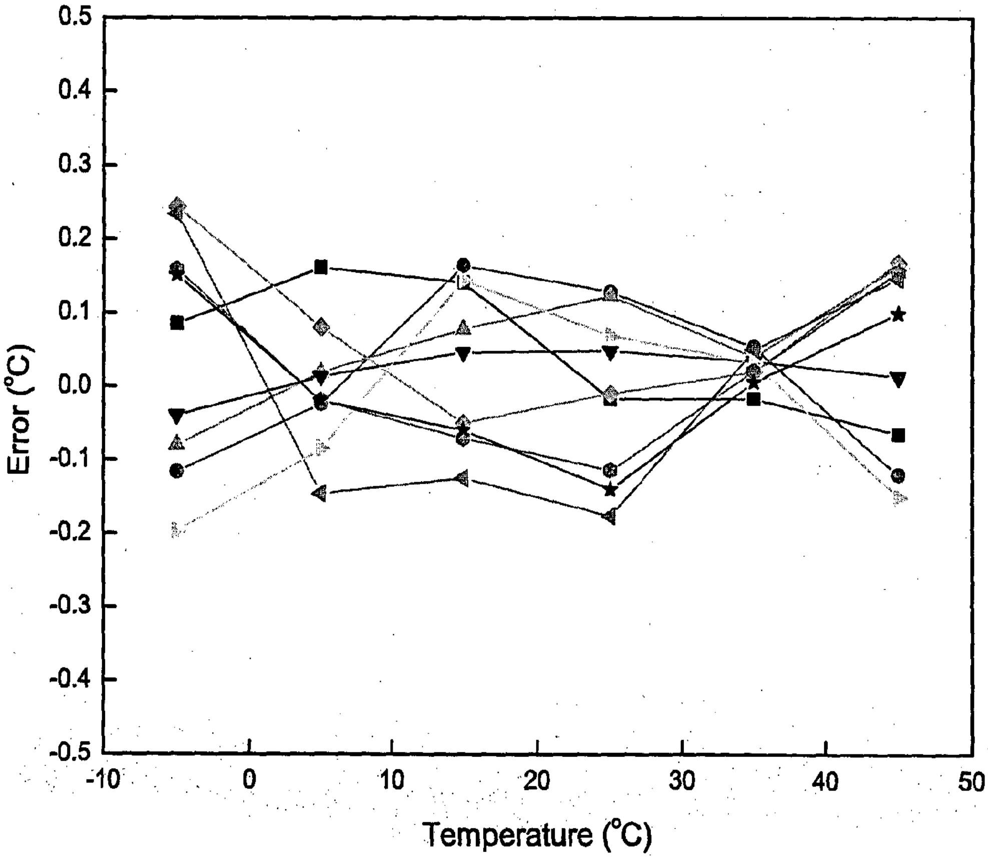

Error (°C)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-10
0
10
20
30
40
50
Temperature (°C)

FIG. 8B

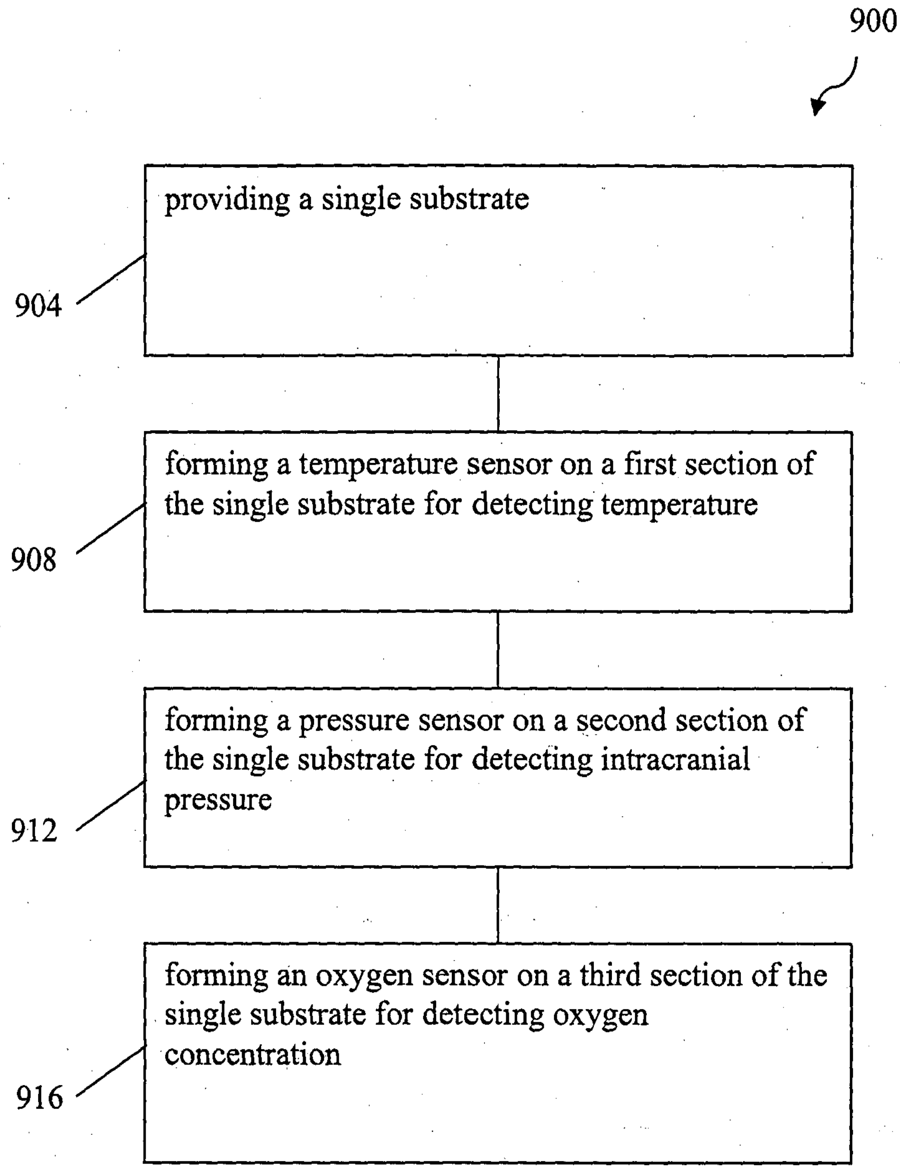

900
providing a single substrate
904
forming a temperature sensor on a first section of the single substrate for detecting temperature
908
forming a pressure sensor on a second section of the single substrate for detecting intracranial pressure
912
forming an oxygen sensor on a third section of the single substrate for detecting oxygen concentration
916

FIG. 9

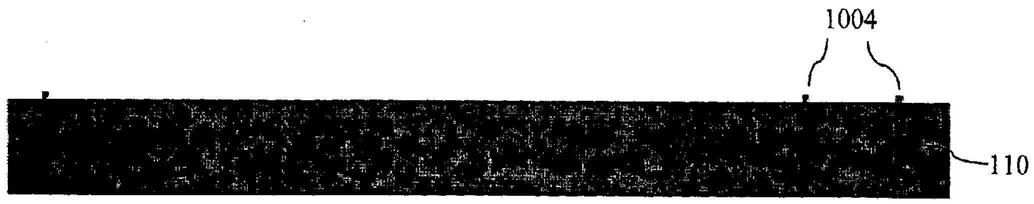


FIG. 10A

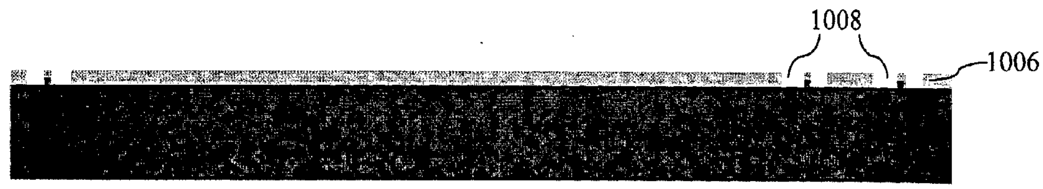


FIG. 10B

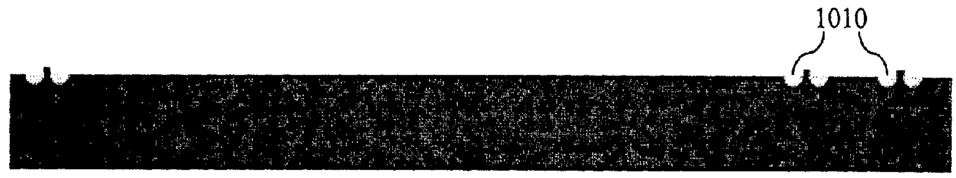


FIG. 10C

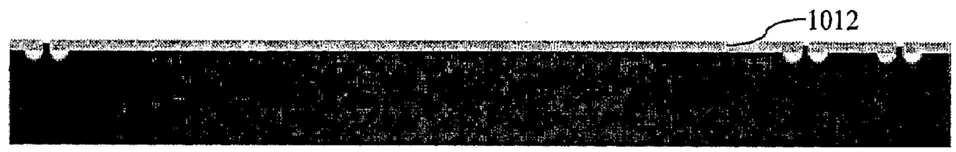


FIG. 10D

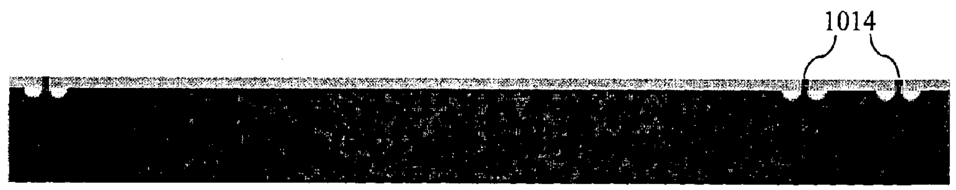


FIG. 10E

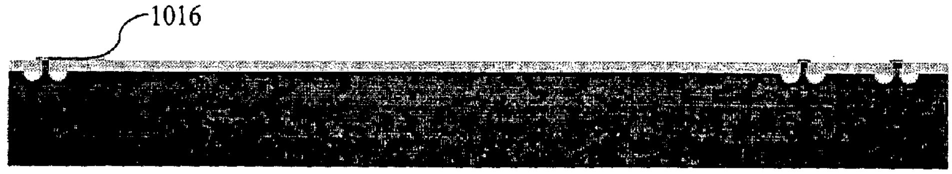


FIG. 10F

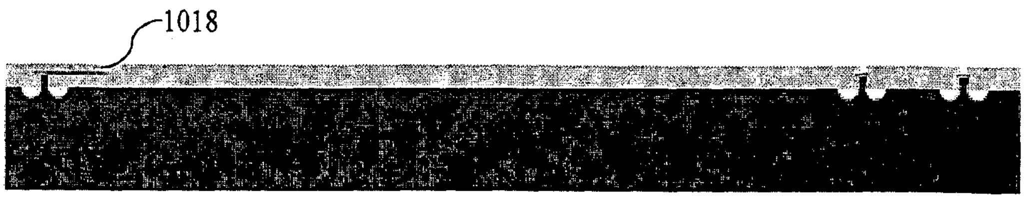


FIG. 10G

FIG. 10H

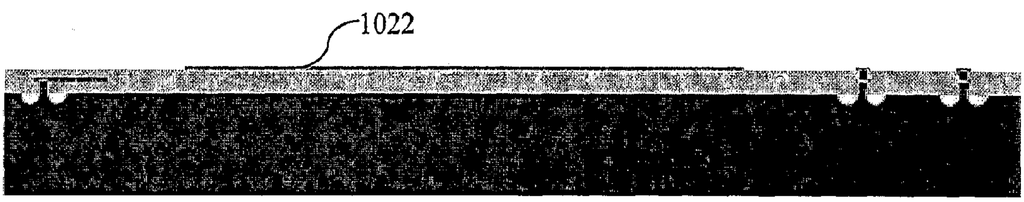


FIG. 10I

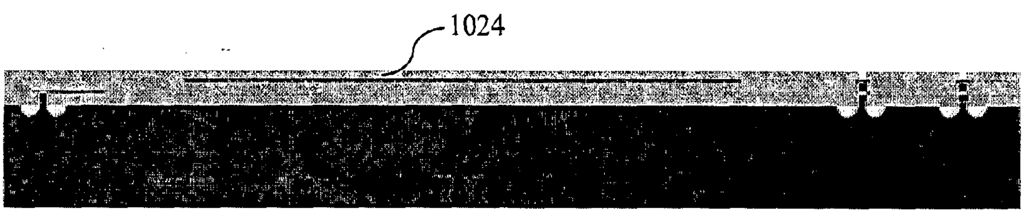


FIG. 10J

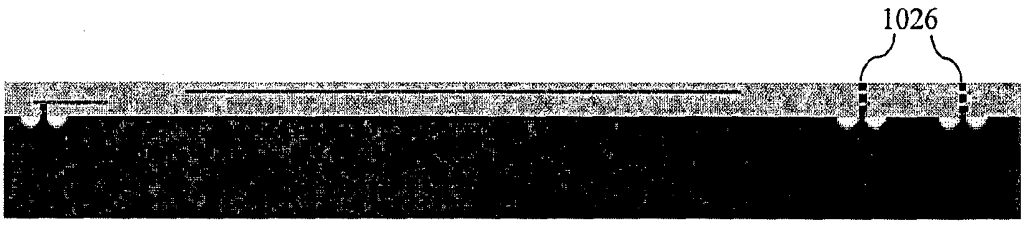


FIG. 10K

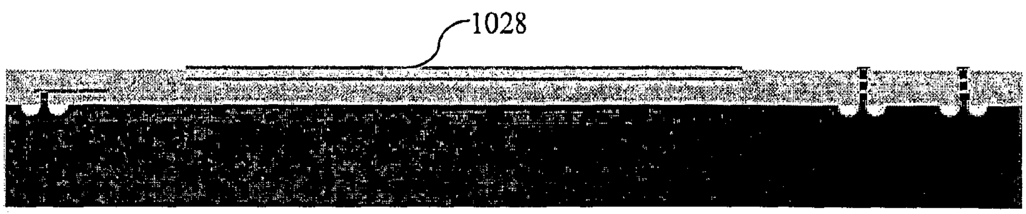


FIG. 10L

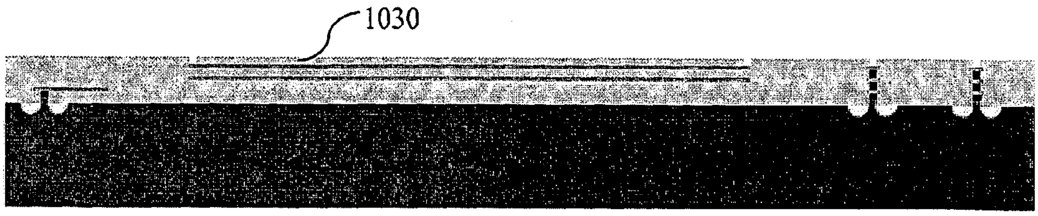


FIG. 10M

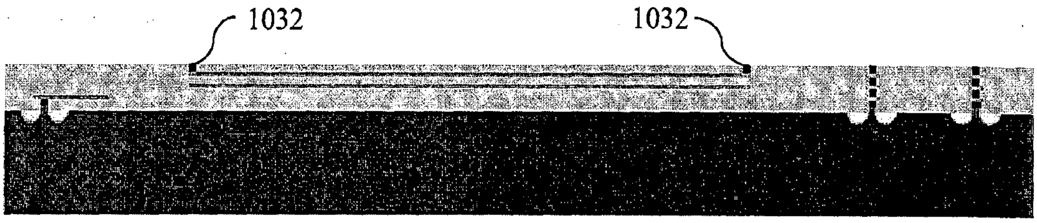


FIG. 10N

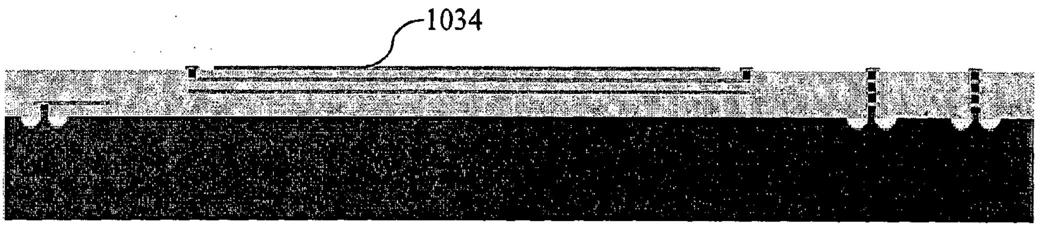


FIG. 10O

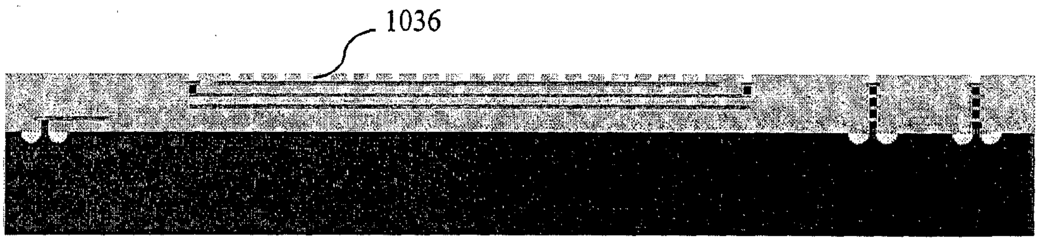


FIG. 10P

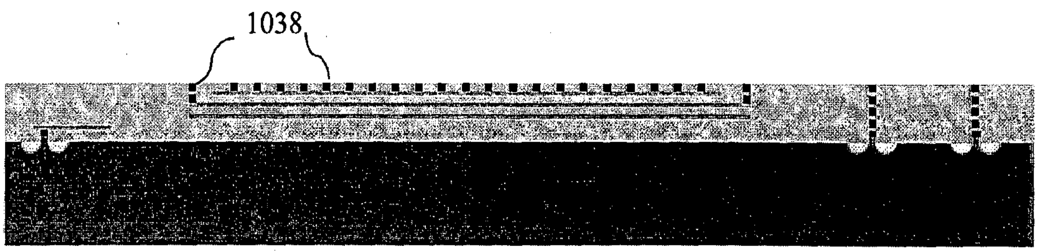


FIG. 10Q

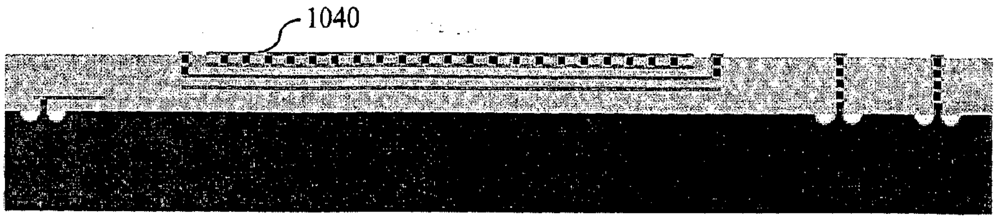


FIG. 10R

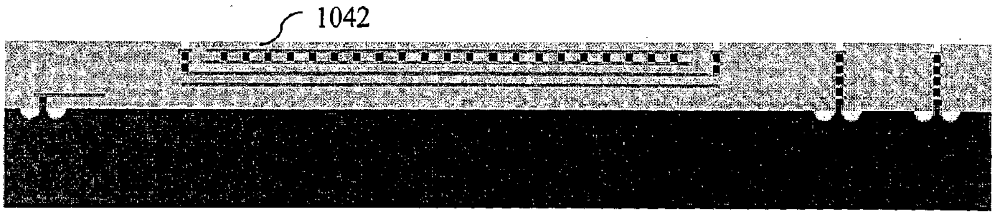


FIG. 10S

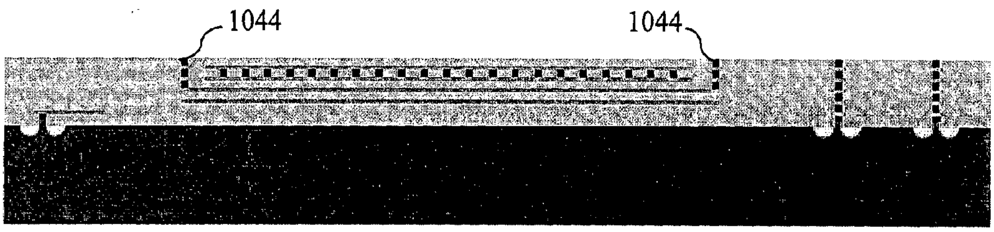


FIG. 10T

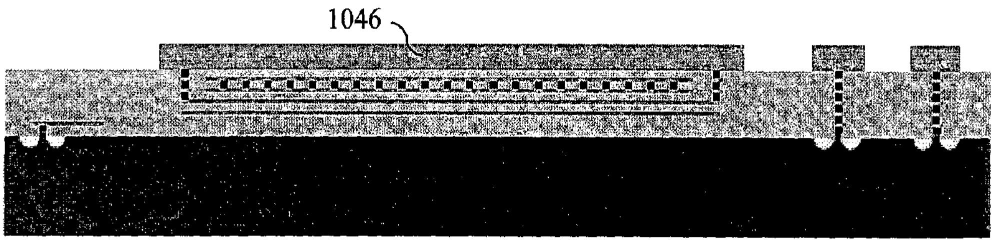


FIG. 10U

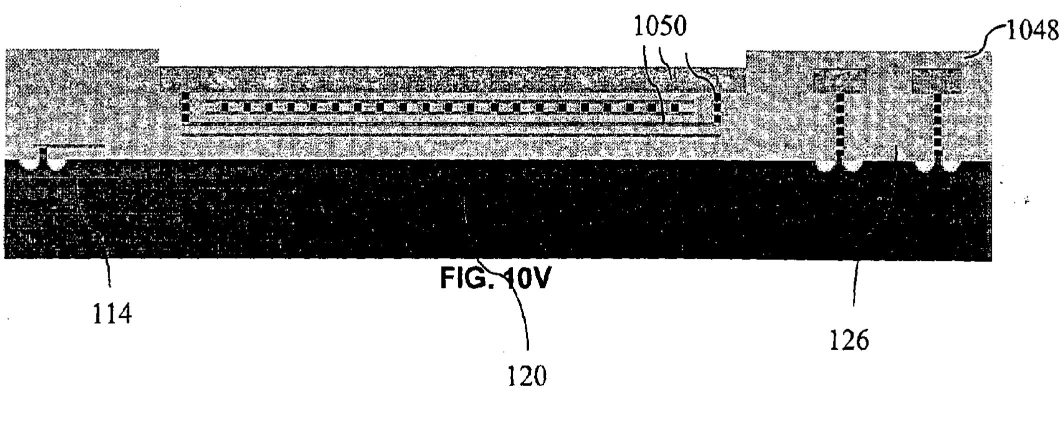


FIG. 10V

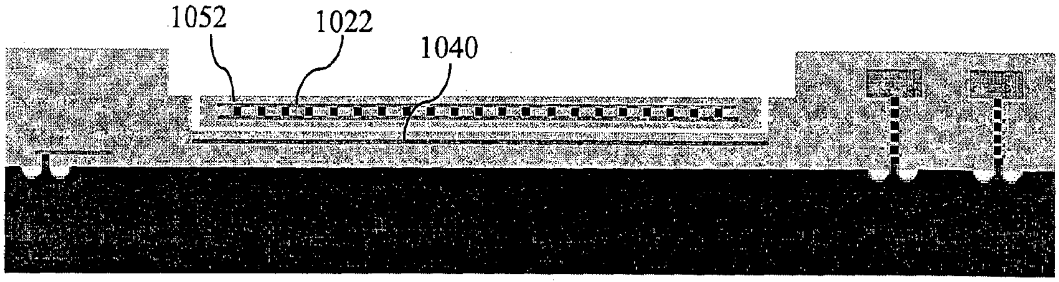


FIG. 10W

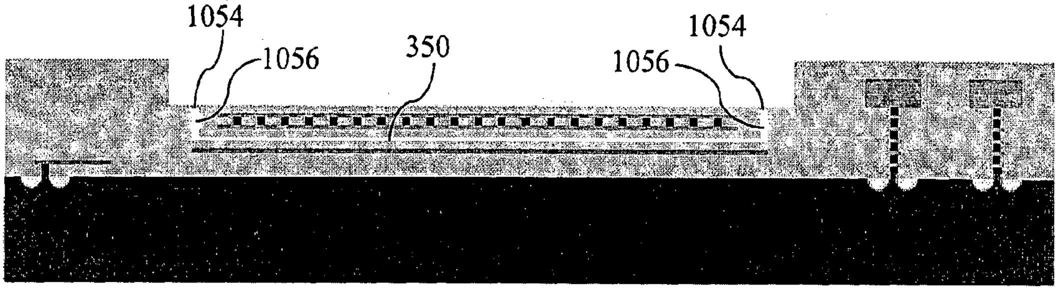


FIG. 10X

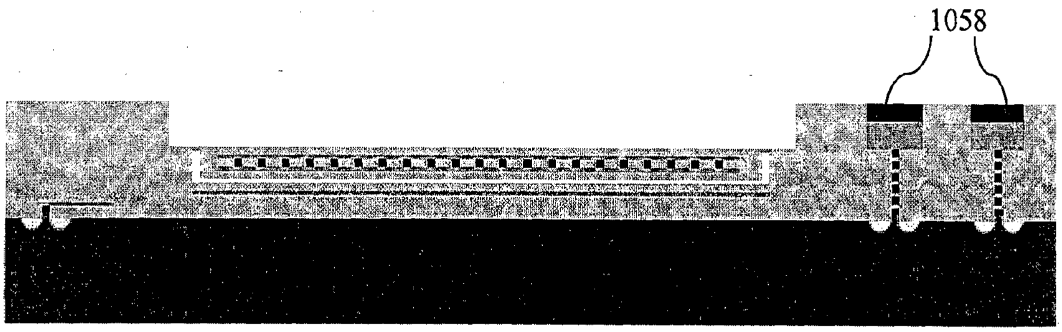


FIG. 10Y

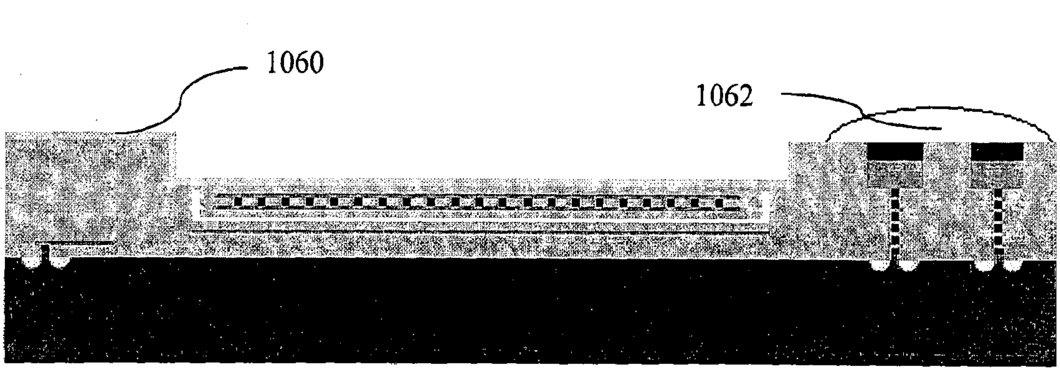


FIG. 10Z

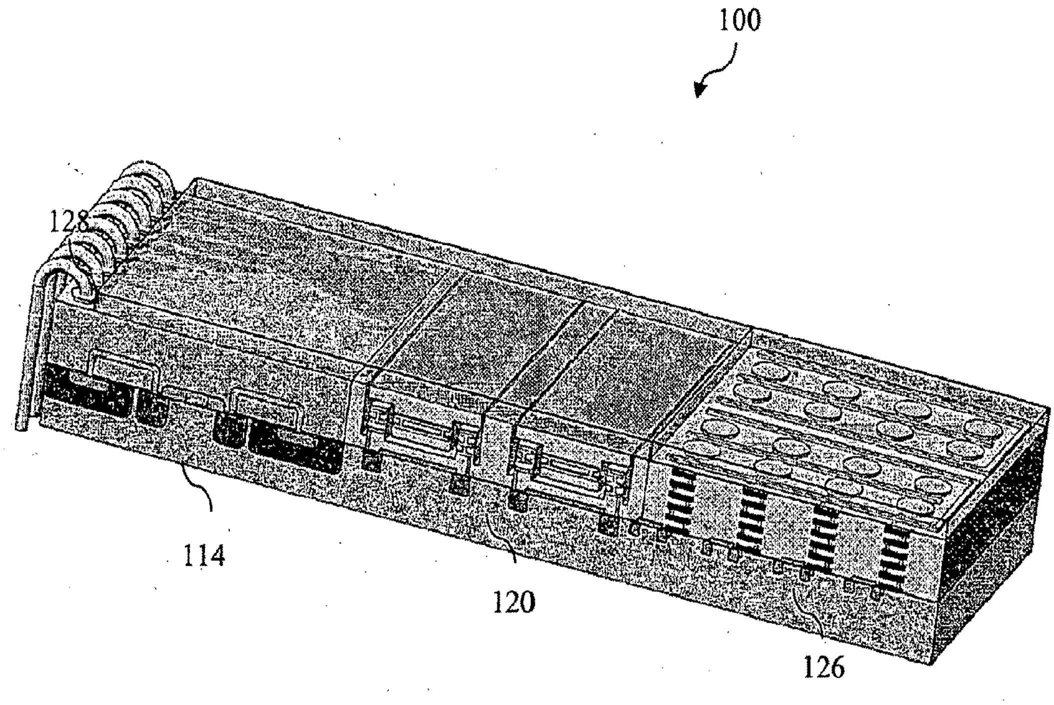


FIG. 11

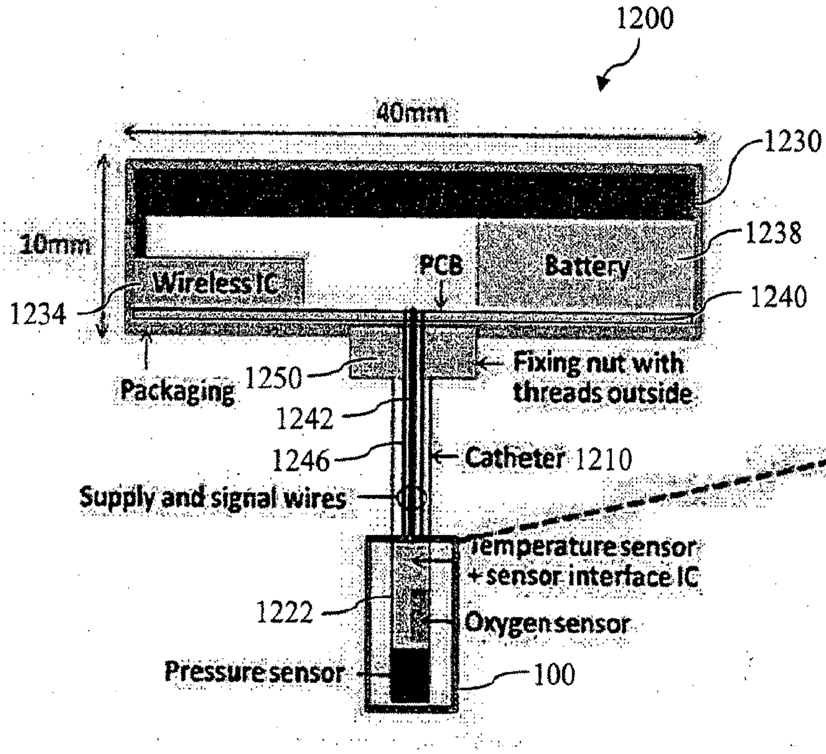


FIG. 12A

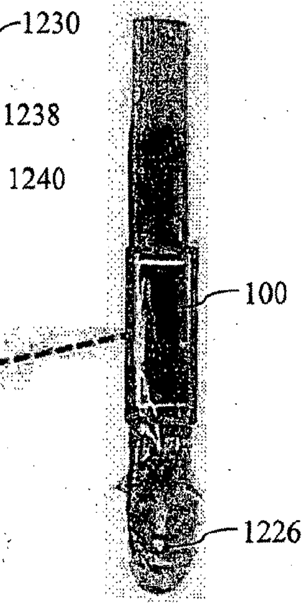
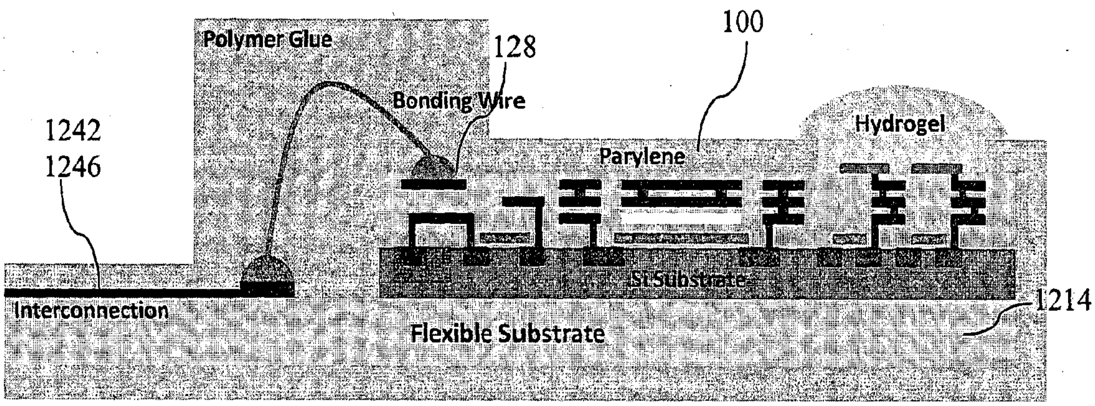


FIG. 12B



Polymer Glue
128
100
Bonding Wire
Hydrogel
1242
1246
Parylene
Si Substrate
Interconnection
1214
Flexible Substrate

FIG. 12C

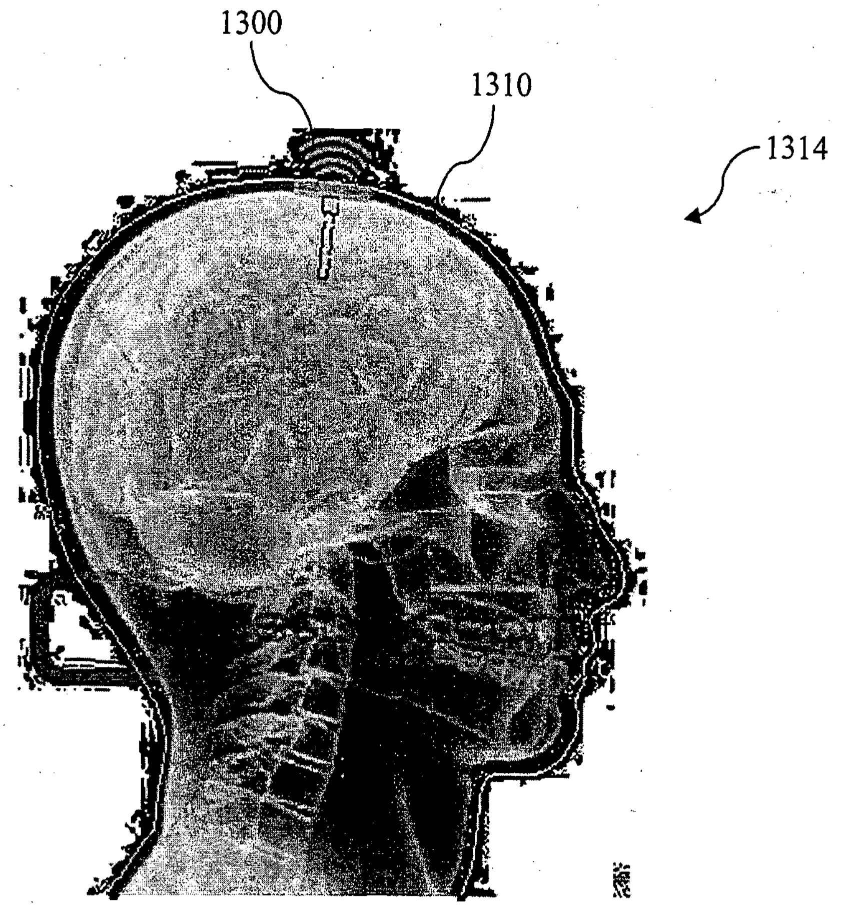


FIG. 13

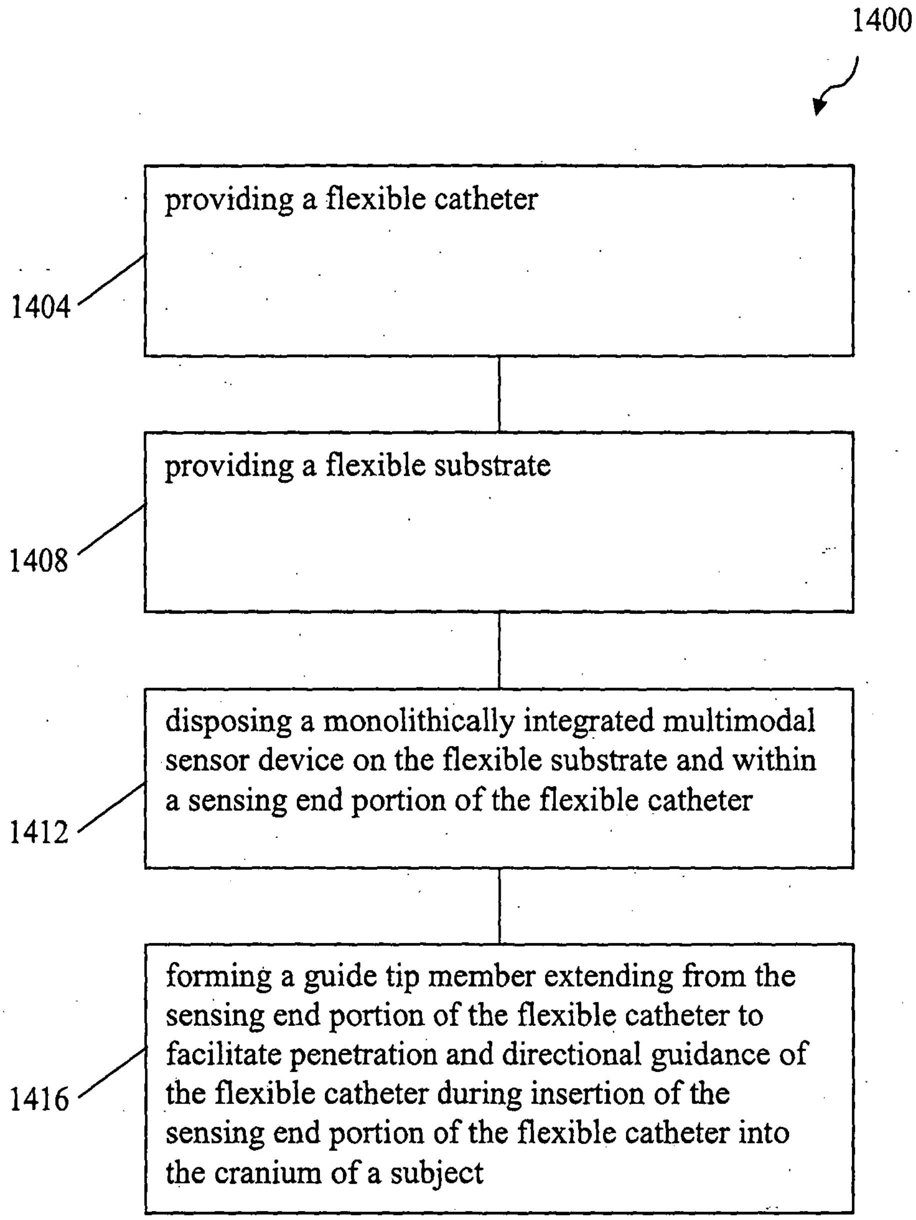

1400
providing a flexible catheter
1404
providing a flexible substrate
1408
disposing a monolithically integrated multimodal sensor device on the flexible substrate and within a sensing end portion of the flexible catheter
1412
forming a guide tip member extending from the sensing end portion of the flexible catheter to facilitate penetration and directional guidance of the flexible catheter during insertion of the sensing end portion of the flexible catheter into the cranium of a subject
1416

FIG. 14

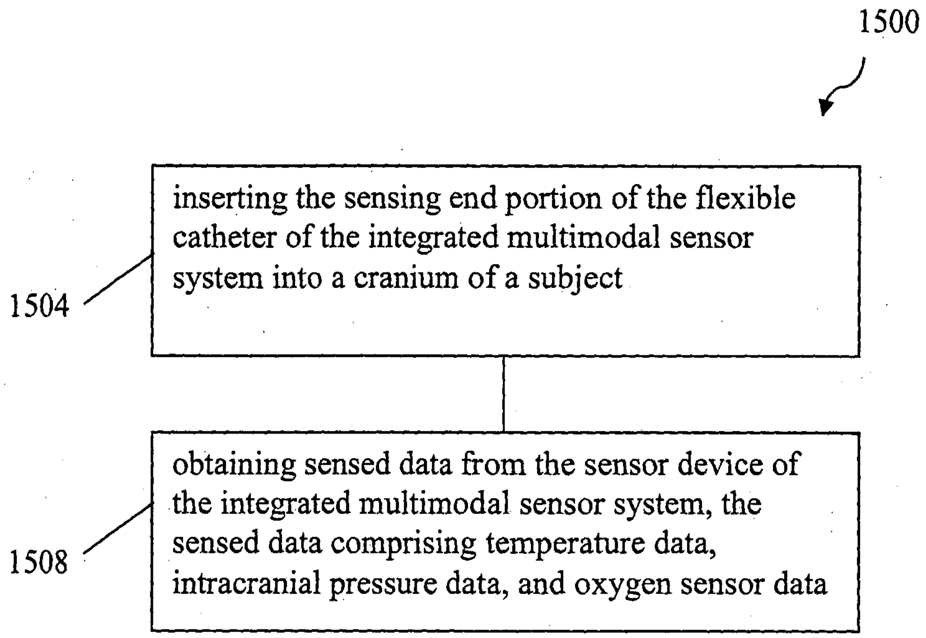

1500
1504
inserting the sensing end portion of the flexible catheter of the integrated multimodal sensor system into a cranium of a subject
1508
obtaining sensed data from the sensor device of the integrated multimodal sensor system, the sensed data comprising temperature data, intracranial pressure data, and oxygen sensor data

FIG. 15

INTEGRATED MULTIMODAL SENSOR DEVICE FOR INTRACRANIAL NEUROMONITORING

FIELD OF INVENTION

[0001] The present invention generally relates to an integrated multimodal sensor device for intracranial neuromonitoring, a multimodal sensor system for intracranial neuromonitoring comprising the integrated multimodal sensor device, and methods of fabrication thereof.

BACKGROUND

[0002] Traumatic brain injury (TBI) is a worldwide phenomenon that has devastating consequences to the patients and the society. The key to TBI management is the capability to control the intracranial pressure (ICP) through accurate monitoring the intracranial pressure, brain oxygenation, and brain temperature in the critical period. Any sudden increase in ICP have to be released either through the drainage of the excess cerebrospinal fluid or by chemotherapy. In a conventional TBI management, standalone pressure sensors, oxygen sensors, and temperature sensors in forms of miniaturized catheters are widely used in intensive care units. An external bolt system is typically used to attach the sensors to the skull to grasp the implanted catheters firmly in the patient's head. Custom data acquisition equipment may then be connected to the catheters directly through the bolt system for signal processing and real-time display of the sensed data from the sensors.

[0003] Practically, with the above-described approach, the inserted bolt size (thus the burr hole size) cannot be made small as it has to hold the 3 implanted catheters, and this extra space is more susceptible to bleeding and infection. Furthermore, the individual catheters are configured as a sensing device only, therefore signal conditioning and processing are done entirely by the external equipment.

[0004] A need therefore exists to provide a sensor device for intracranial neuromonitoring which seeks to overcome, or at least ameliorate, one or more of the deficiencies of the conventional art mentioned above. It is against this background that the present invention has been developed.

SUMMARY

[0005] According to a first aspect of the present invention, there is provided a monolithically integrated multimodal sensor device for intracranial neuromonitoring, the sensor device comprising:

[0006] a single substrate;

[0007] a temperature sensor formed on a first portion of the single substrate for detecting temperature;

[0008] a pressure sensor formed on a second portion of the single substrate for detecting intracranial pressure; and

[0009] an oxygen sensor formed on a third portion of the single substrate for detecting oxygen concentration,

[0010] wherein sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device.

[0011] Preferably, the sensing portion of the temperature sensor is formed at the single substrate, the sensing portion of the pressure sensor is formed at intra-metal layers of the sensor device, and the sensing portion of the oxygen sensor is formed at a top metal layer of the sensor device.

[0012] Preferably, the temperature sensor comprises one or more transistors, and the sensing portion of the temperature sensor includes an active region of the respective one or more transistors.

[0013] Preferably, the transistor is a parasitic vertical PNP transistor.

[0014] Preferably, the pressure sensor comprises one or more capacitive MEMS pressure sensors, and the sensing portion of the pressure sensor includes a movable electrode of the respective one or more capacitive MEMS pressure sensors.

[0015] Preferably, the oxygen sensor comprises a switchable array of oxygen sensor elements, and the sensing portion of the oxygen sensor comprises a working electrode of the respective oxygen sensor elements.

[0016] Preferably, the oxygen sensor is configured to switch to one of the oxygen sensor elements to provide the oxygen level reading which satisfies a predetermined sensitivity level.

[0017] Preferably, the sensor device further comprises one or more application-specific integrated circuits formed on the single substrate for processing readings from the temperature sensor, the oxygen sensor, and the oxygen sensor.

[0018] According to a second aspect of the present invention, there is provided a method of fabricating a monolithically integrated multimodal sensor device for intracranial neuromonitoring, the method comprising:

[0019] providing a single substrate;

[0020] forming a temperature sensor on a first portion of the single substrate for detecting temperature;

[0021] forming a pressure sensor on a second portion of the single substrate for detecting intracranial pressure; and

[0022] forming an oxygen sensor on a third portion of the single substrate for detecting oxygen concentration,

[0023] wherein sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device.

[0024] Preferably, the sensing portion of the temperature sensor is formed at the single substrate, the sensing portion of the pressure sensor is formed at intra-metal layers of the sensor device, and the sensing portion of the oxygen sensor is formed at a top metal layer of the sensor device.

[0025] Preferably, the temperature sensor comprises one or more transistors, and the sensing portion of the temperature sensor includes an active region of the respective one or more transistors.

[0026] Preferably, the transistor is a parasitic vertical PNP transistor.

[0027] Preferably, the pressure sensor comprises one or more capacitive MEMS pressure sensors, and the sensing portion of the pressure sensor includes a movable electrode of the respective one or more capacitive MEMS pressure sensors.

[0028] Preferably, the oxygen sensor comprises a switchable array of oxygen sensor elements, and the sensing portion of the oxygen sensor comprises a working electrode of the respective oxygen sensor elements.

[0029] Preferably, the oxygen sensor is configured to switch to one of the oxygen sensor elements to provide the oxygen level reading which satisfies a predetermined sensitivity level.

[0030] Preferably, the method further comprises forming one or more application-specific integrated circuits on the single substrate for processing readings from the temperature sensor, the oxygen sensor, and the oxygen sensor.

[0031] According to a third aspect of the present invention, there is provided an integrated multimodal sensor system for intracranial neuromonitoring, the sensor system comprising:

[0032] a flexible catheter;

[0033] a flexible substrate;

[0034] a monolithically integrated multimodal sensor device according to the above-described first aspect of the present invention disposed on the flexible substrate and within a sensing end portion of the flexible catheter; and

[0035] a guide tip member extending from the sensing end portion of the flexible catheter to facilitate penetration and directional guidance of the flexible catheter during insertion of the sensing end portion of the flexible catheter into the cranium.

[0036] Preferably, the guide tip member has a rounded tip and is made of silicone.

[0037] Preferably, the sensor system further comprises a housing including therein a wireless communication module for receiving sensed data from the sensor device and an antenna for transmitting the sensed data wirelessly to one or more remote extracranial devices.

[0038] According to a fourth aspect of the present invention, there is provided a method of forming an integrated multimodal sensor system for intracranial neuromonitoring, the method comprising:

[0039] providing a flexible catheter;

[0040] providing a flexible substrate;

[0041] disposing a monolithically integrated multimodal sensor device according to the above-described first aspect of the present invention on the flexible substrate and within a sensing end portion of the flexible catheter; and

[0042] forming a guide tip member extending from the sensing end portion of the flexible catheter to facilitate penetration and directional guidance of the flexible catheter during insertion of the sensing end portion of the flexible catheter into the cranium.

BRIEF DESCRIPTION OF THE DRAWINGS

[0043] Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

[0044] FIG. **1**A depicts a schematic top view of an example monolithically integrated multimodal sensor device for intracranial neuromonitoring according to an example embodiment of the present invention;

[0045] FIG. **1**B depicts a schematic cross-sectional view of the example sensor device shown in FIG. **1**A;

[0046] FIG. **2** depicts a schematic diagram of an example temperature sensor circuit according to an embodiment of the present invention;

[0047] FIG. **3**A depicts a cross-sectional view of one example capacitive MEMS pressure sensor according to an embodiment of the present invention;

[0048] FIGS. **3**B and **3**C depict the top view and the cross-sectional view of the released membrane of the pressure sensor captured in the scanning electro-microphotograph (SEM), respectively;

[0049] FIG. **4** depicts an exemplary the oxygen sensor configured as a 3-electrode system according to an embodiment of the present invention;

[0050] FIG. **5** depicts a schematic diagram of an exemplary ASIC integrally formed on the substrate according to an embodiment of the present invention;

[0051] FIG. **6**A depicts a graph showing the output response of the pressure sensor versus the pressure applied in an experiment;

[0052] FIG. **6**B depicts a graph showing the measured result of pressure sensor capacitance mismatch calibration;

[0053] FIG. **7**A depicts a graph showing the output response of the oxygen sensor versus dissolved oxygen concentration in an experiment;

[0054] FIG. **7**B depicts a graph showing the measured transient response of the oxygen sensor in an aqueous solution from nitrogen-saturated condition to air-saturated condition;

[0055] FIG. **8**A depicts a graph illustrating the linear output response of the temperature sensor in an experiment;

[0056] FIG. **8**B depicts a graph illustrating the temperature inaccuracy of multiple temperature sensors over the temperature range from −5° C. to 45° C. in an experiment;

[0057] FIG. **9** depicts an overview of a method of fabricating the monolithically integrated multimodal sensor device for intracranial neuromonitoring according to an embodiment of the present invention;

[0058] FIGS. **10**A to **10**Z shows the steps in fabricating the integrated multimodal sensor device according to an example embodiment of the present invention;

[0059] FIG. **11** an example completed sensor device (or sensor chip) fabricated according to an example embodiment of the present invention;

[0060] FIGS. **12**A to **12**C depict the sensor device packaged for in-vivo application (an integrated multimodal sensor system) according to an example embodiment of the present invention;

[0061] FIG. **13** depicts an example of the sensor system being used for in-vivo application;

[0062] FIG. **14** depicts an overview of a method of fabricating the sensor system for intracranial neuromonitoring according to an embodiment of the present invention; and

[0063] FIG. **15** depicts an overview of a method of intracranial neuromonitoring using the integrated multimodal sensor system for in-vivo application according to an embodiment of the present invention.

DETAILED DESCRIPTION

[0064] Intracranial neuromonitoring of various physiologic parameters is critical in neurological disorders such as traumatic brain injury (TBI), hydrocephalus and tumours that can cause changes in the pressure within the skull of a subject. Example embodiments of the present invention provide a monolithically integrated multimodal sensor device for intracranial neuromonitoring, including a temperature sensor for detecting intracranial temperature, a pressure sensor for detecting intracranial pressure, and an oxygen sensor for detecting oxygen concentration. In particular, in the example embodiments, the temperature sensor, the pressure sensor, and the oxygen sensor are integrated on a single substrate. This advantageously enables the sensor device having intracranial temperature, intracranial pressure and oxygen concentration sensing capabilities to be provided with a single catheter, thus eliminating the need to provide multiple catheters for obtaining multiple physiologic parameters. As a result, the size of the bolt or burr hole required to perform intracranial neuromonitoring can be minimised, thus making it less susceptible to bleeding and infection. The overall intracranial neuromonitoring process is also greatly simplified since, for example, less catheters are involved.

[0065] FIG. **1**A depicts a schematic top view of an example monolithically integrated multimodal sensor device **100** for intracranial neuromonitoring according to an example embodiment of the present invention. FIG. **1**B depicts a schematic cross-sectional view of the example sensor device **100**. As shown, the sensor device **100** comprises a single substrate (preferably, silicon substrate) **110**, a temperature sensor **114** formed on a first portion **116** of the single substrate **110** for detecting intracranial temperature, a pressure sensor **120** formed on a second portion **122** of the single substrate **110** for detecting intracranial pressure, and an oxygen sensor **126** formed on a third portion **128** of the single substrate **110** for detecting oxygen concentration. In particular, sensing portions **130**, **132**, **134** of the temperature sensor **114**, the pressure sensor **120** and the oxygen sensor **126**, respectively, are formed at different layers of the sensor device **100**.

[0066] In the example embodiment as shown in FIG. **1**B, the sensing portion **130** of the temperature sensor **114** is formed at the single substrate **110**, the sensing portion **132** of the pressure sensor **120** is formed at intra-metal layers **138** of the sensor device **100**, and the sensing portion **134** of the oxygen sensor **126** is formed at a top metal layer **142** of the sensor device **100**. In this regard, forming the sensing portions **130**, **132**, **134** of the three sensors **114**, **120**, **126** at different layers of the sensor device **100** enables the three sensors **114**, **120**, **126** to be formed integrally on a single substrate **110** (i.e., integrated into a single chip) using a customized integrated fabrication flow. The steps in fabricating the integrated multimodal sensor device **100** will be described in detail later below with reference to FIGS. **10**A to **10**Z.

[0067] In an example embodiment, the temperature sensor **114** is realised by one or more transistors, preferably, parasitic vertical PNP transistors. As an example, FIG. **2** shows a schematic diagram of an example temperature sensor circuit **200** which includes a PTAT (Proportional To Absolute Temperature) current generator **204**, a bandgap reference **208** and a V_{BE} amplifier **212**. In the PTAT current generator **204**, two identical PNP transistors Q_1 **230** and Q_2 **232** are biased in a current ratio of 1 to 5. The difference of the base emitter voltage V_{BE1} **234** and V_{BE2} **236** is a PTAT voltage ΔV_{BE} **238** which can be sensed by resistor R_1 **240** and feedback to the chopper stabilized error amplifier A_1 **242**. The current ratio of 1 to 5 is implemented by randomly scrambling the PMOS current sink **243** through dynamic element matching (DEM). As a result, the impact of the device mismatch to the circuit operation point is minimized, and the current flowing through the resistor R_1 **240** is a PTAT current I_P **244**. This PTAT current source **244** is mirrored to bias a NPN transistor Q_3 **246** having an identical size as transistors Q_1 **230** and Q_2 **232**, and produces a PTAT voltage drop across the resistor R_2 **248**. The bandgap voltage V_{BG} **250** is obtained by summing the base-emitter voltage V_{BE3} **252** and the PTAT voltage across R_2 **248**. The process spread of the saturation current, the finite value of the forward current gain, and the base resistance of transistor Q_3 **246** all contribute to base emitter voltage V_{BE3} **252** mismatch. In a preferred embodiment, a one-point calibration is implemented to compensate the V_{BE3} **252** mismatch. A 5-bit on-chip resistor trimming network including resistors (R_{t1-t32}) **260** and switches (SK_{t1-t32}) **262** is used to provide coarse V_{BE3} calibration with 32 steps of PTAT voltage tuning at room temperature.

[0068] In the example embodiment, the sensing portion **130** of the temperature sensor **114** includes an active region of the respective one or more transistors. Preferably, the transistors are fabricated in the silicon substrate **110** by CMOS foundries and the operation of a PNP transistor can be expressed by the following Equation:

$$I_c = I_s \exp\left(\frac{V_{BE}}{V_T}\right) \tag{1}$$

where I_s is the saturation current, V_{BE} is the base emitter voltage, V_T is the thermal voltage, and I_c is the collector current of the bipolar transistor. As can be seen from Equation 1, the saturation current (I_s) has a strong temperature dependency, and the temperature sensor **114** has been found to exhibit a temperature sensitivity of about −2 mV/° C. with respect to V_{BE}.

[0069] However, fabrication mismatch may exists in standard CMOS process, and it has been found that the model as shown in Equation 1 is only good as long as the process parameters such as the saturation current (I_s) are well controlled. But the limited current gain associated with the PNP transistor, the finite value of the base resistance, the high level injection, and the Early effect all affect the accuracy and the sensitivity of the temperature sensor **114**. Therefore, in a preferred embodiment, V_{BE} calibration is implemented to improve the accuracy of the temperature sensor **114** as for example described above with reference to FIG. **2** where resistor trimming is the chosen technique to achieve the V_{BE} calibration. Various trimming circuit implementations have been disclosed in the art to address temperature sensor mismatches and yield good accuracies. Therefore, the present invention is not limited to the trimming circuit as shown in FIG. **2** and a person skilled in the art would be able to apply any other appropriate trimming circuit known in the art to the temperature sensor **114** to improve sensing accuracy. The steps in fabricating the temperature sensor **114** will be described in detail later below as part of the process of fabricating the integrated multimodal sensor device **100**.

[0070] In an example embodiment, the pressure sensor **120** is realised by one or more capacitive MEMS pressure sensors in CMOS. A cross-sectional view of one example capacitive MEMS pressure sensor **300** is schematically illustrated in FIG. **3**A. The pressure sensor **300** is advantageously simple as it involves a front side release only. In the example embodiment, the MEMS configuration utilizes two metals layers **314**, **315** (M4 and M5) and three intra-metal dielectric layers **310**, **311**, **312** (IMD3, IMD4, and IMD**5**) (e.g., SiO_2) for the movable electrode **318**, and one metal layer **326** (M2) and two intra-metal dielectric layers **327** (IMD2 and IMD1) for the stationary electrode **322** under the movable electrode **318**. In order to create room for the movable electrode **318**, a first via **330**, a second via **334** and a third via **338** have to be etched away first and subsequently the intra-metal layer under the movable electrode **318** (i.e., M3 to form a cavity **350**). In this example, the sensing portion **132** of the pressure sensor **120** includes the movable electrode **318** of the respective one or more capacitive MEMS pressure sensors. For example, the etchant involved is a mixture of H_2SO_4+H_2O_2 (2:1) heated at 100° C. over 120 minutes. The steps in fabricating the pressure sensor **300** will be described in detail later below as part of the process of fabricating the integrated multimodal sensor device **100**.

[0071] The top view and the cross-sectional view of the released membrane are captured in the scanning electro-microphotograph (SEM) and illustrated in FIGS. **3**B and **3**C, respectively. In FIG. **3**C, the existence of the cavity **350** can be observed (which is shown in a dark shading) between the top plate **354** and the bottom plate **358**. It can also be observed that the non-etched via **362** (which is shown in a light shading) connecting metal layer M**4** **314** and metal layer M**5** **315** within the top plate **354**. The movable electrode **318** is formed using metal layers M**4** **314** and M**5** **315** and the vias **45** **334** have two functions depending on the layout location. A first function is to serve as a path to release the structure (that is, to etch away the materials that metals layers and vias are made of, for example, Aluminium (Al) and Tungsten (W), respectively) and a second function is to connect M**4** **314** and M**5** **314** layers. As a final step, a protective polymer coating material **150** (preferably, Parylene-C) is patterned to encapsulate the pressure sensor's active area **132** using standard lithograph. In an example implementation, the MEMS pressure sensor **120** is configured as an array of 9 capacitors with a trimming circuit to achieve good accuracy and sensitivity. Various trimming circuit implementations have been disclosed to address pressure sensor mismatches and yield good accuracies. A person skilled in the art would be able to apply an appropriate trimming circuit known in the art to the pressure sensor **120** to improve sensing accuracy and thus it is not necessary to be described herein.

[0072] In an embodiment, the oxygen sensor **126** comprises a switchable array of oxygen sensor elements **410**. A top view of oxygen sensor **126** in CMOS made up of an array of 16 oxygen sensor elements **410** is illustrated in FIG. **4**. Preferably, the oxygen sensor elements **410** are clark-type dissolved oxygen sensors. FIG. **4** illustrates the oxygen sensor **126** configured as a 3-electrode system (i.e., working electrode **410**, counter electrode **414**, and reference electrode **418**). It will be appreciated that the oxygen sensor **126** of the present invention is not limited to a 3-electrode system. For example, the oxygen sensor **126** may be configured as a 2-electrode system (i.e., working electrode and reference electrode). In this embodiment, the sensing portion **134** of the oxygen sensor **126** comprises the oxygen sensor elements (working electrode) **410**.

[0073] In an example embodiment, to fabricate the working electrode **410** on the top metal layer **142** of the sensor device **100**, platinum is used as the raw material to form the working electrode **410**. The working electrode **410** can be attached to the CMOS top metal layer **142** (e.g., aluminium) through a layer of 20 nm thick titanium in between the platinum working electrode **410** and the top metal layer **142**. The actual physical shape of the working electrode **410** as shown in FIG. **4** can be patterned by E-beam evaporator together with lift-off. To maximize the working electrode **410** sensitivity, the following Equation can be used to relate the sensitivity with the area of working electrode **410**:

$$i = \frac{nA_s FDC_{DO}}{\delta} \quad (2)$$

where n is the number of exchanged electrons, A_s is the area of the working electrode **410**, F is Faraday's constant, D is the diffusivity, C_{DO} is the dissolved oxygen concentration in a given sample, 5 is the thickness of the selective permeable membrane, and i is the reduction current. By way of example only, the unit size of 25 μm×50 μm working electrode **410**, approximately 250 pA reduction current can be generated for every mmHg dissolved oxygen at room temperature.

[0074] In an embodiment, specific polymers 154, whose physical structures are selective permeable, are used to encapsulate the oxygen sensor **126**. For instance, a nickel-salen polymer can be used as a solid electrolyte, and this polymer was found to be able to increase the sensitivity of the platinum working electrode **410**. On the other hand, NAFION which is commercially available can be chosen as a solid electrolyte. NAFION has been used as a solid electrolyte which permits oxygen transport across its structure. Unfortunately, NAFION deposition on the platinum electrode **410** cannot be done using similar CMOS processing. Instead, it is usually deposited in drop-cast which is subjected to coating thickness mismatch.

[0075] All the sensors **114**, **120**, **126** fabricated in the sensor device **100** are calibrated to achieve a certain degree of accuracy. For instance, the specifications of both the pressure sensor **120** and the oxygen sensor **126** are configured to achieve an inaccuracy of ±1 mmHg whereas the temperature sensor **114** is ±0.2° C. for the typical sensing range. Due to the post-processing mismatch, the fabricated sensors suffer a certain degree of mismatch relative to its operating parameters. In the capacitive MEMS pressure sensor **120** or the PNP-based temperature sensor **114**, sensor mismatches are relatively well modelled. As mentioned hereinbefore, various trimming circuit implementations have been disclosed to address pressure sensor and temperature sensor mismatches and yield good accuracies. Therefore, a person skilled in the art would be able to apply appropriate trimming circuits known in the art to the temperature sensor **114** and the pressure sensor **120** to improve sensing accuracy.

[0076] But on the other hand, the challenge in calibrating the electrochemical oxygen sensor **126** comes from the non-standard fabrication of the oxygen sensor **126**. Specifically, the non-standard fabrication in developing the oxygen sensor **126** is the hydrogel **154** deposition, for example, the deposition of NAFION by drop-cast as mentioned above. The coating thickness of this hydrogel **154** is highly subjected to mismatch which is a significant factor resulting in the inaccuracy of the oxygen sensors **126**. In the example embodiment, the oxygen sensor **126** is configured with sensor calibration. In particular, the oxygen sensor **126** comprises a switchable array of oxygen sensor elements **410** is provided to address the above problem. For example, the oxygen sensor **126** comprises 16 switchable working electrodes **410** sharing a common electrode **418** and a reference electrode **414** as illustrated in FIG. **4**. In particular, the oxygen sensor **126** is configured to switch to one of the oxygen sensor elements **410** to provide the oxygen level reading which satisfies a predetermined sensitivity level. The specific working electrode element **410** can be activated by evaluating its sensitivity during the sensor calibration procedure. Therefore, the sensitivity of working electrode **410** can be recorded and evaluated against the target sensitivity. If there are more than a single working electrode **410** which can achieve the target sensitivity, the array implementation adds a back up to the system such that any specific sensor failure can be replaced by an available working electrode element **410**.

[0077] In an embodiment, the sensor device **100** further comprises one or more application-specific integrated circuits (ASIC) integrally formed on the single substrate **110** for processing readings from the temperature sensor, the pressure sensor, and the oxygen sensor. FIG. **5** depicts a schematic diagram of an exemplary ASIC **500** integrally formed on the single substrate **110**. The ASIC **500** comprises a pressure sensor interface circuit **504** including a capacitance-to-voltage converter (CVC) for processing readings from the pressure sensor **120**, an oxygen sensor interface circuit **508** including a potentiostat and a transimpedance amplifier (TIA) for processing readings from the oxygen sensor **126**, and a temperature sensor interface circuit **512** including a bandgap reference and a proportional-to-absolute-temperature (PTAT) voltage generator for processing readings from the temperature sensor **114**. In the example embodiment, since the pressure, oxygen and temperature signals have low-frequency variation, the outputs of the sensor interface circuits **504**, **508**, **512** can be multiplexed to share a single 10-bit SAR ADC (successive approximation analog-to-digital converter) **520** for signal digitization. A digital controller **524** is provided for converting the ADC **520** output to a serial bit stream for communicating with the external devices such as an external data logger.

[0078] In an experiment, the capacitive MEMS pressure sensor **120** is configured as a capacitance to voltage converter (CVC) for direct signal processing, and FIG. **6**A shows the output response of the CVC versus the pressure applied. The linear fit curve has a coefficient of determination (R^2) of 0.9862, indicating good linear response of the sensor circuit and the measured sensitivity is 0.67 mV/mmHg. A 14-bit ADC is able to convert this sensitivity into the required resolution. FIG. **6**B shows the measured result of pressure sensor capacitance mismatch calibration. It is demonstrated that by changing the resistive DAC trimming code with UP/DOWN control, the trimming circuit can cover a linear tuning range from −237.8 fF to +239.9 fF with 0.93-fF resolution.

[0079] In an experiment, the oxygen sensor **126** is configured as a potentiometer, which outputs a current directly proportional to the concentration of oxygen. The current generated is then further converted to a voltage by a transimpedance amplifier. FIG. **7**A is a plot of the output response of the oxygen sensor versus dissolved oxygen concentration and summarizes the measured result of the oxygen sensor **126** performance. Over the measured partial pressure of dissolved oxygen from 10 to 55 mmHg, the linear fit curve has a R^2 of 0.9957 and the measured sensitivity is 0.78 mV/mmHg, which is equivalent to an input sensitivity of 194 pA/mmHg. FIG. **7**B shows the measured transient response of the oxygen sensor **126** in an aqueous solution from nitrogen-saturated condition to air-saturated condition. FIG. **7**B demonstrates the fast response of the oxygen sensor to the change of dissolved oxygen concentration. Again, a 14-bit ADC is able to convert this detected partial pressure of the dissolved oxygen in 1 mmHg resolution.

[0080] In an experiment, the temperature sensor **114** is incorporated in the classical bandgap topology where the output of interest is the base emitter voltage. As the typical sensitivity of the base emitter voltage is about −2 mV/° C., the base emitter voltage is actually connected to a second stage with a gain of 5 to increase the the sensitivity to above 10 mV/° C. In this temperature sensor characterization, 9 chips were evaluated. Since the temperature sensitivity is increased by design, the resolution requirement of the ADC can be reduced from 14 bits to 10 bits. As shown in FIG. **8**A, the temperature sensor **114** has a linear output response with R^2 of 0.9999, the measured output sensitivity is about 11 mV/° C. when the measurement results of 9 chips are averaged. FIG. **8**B illustrates that a temperature inaccuracy of ±0.3° C. is achieved over the temperature range from −5° C. to 45° C. In addition, FIG. **8**B shows that after one-point calibration at 35° C., the inaccuracy of the sensors is bound within ±0.2° C. over the target temperature range of 30° C. to 45° C.

[0081] An overview of a method **900** of fabricating the monolithically integrated multimodal sensor device **100** for intracranial neuromonitoring will now be described according to an embodiment of the present invention with reference to FIG. **9**. The method **900** comprises a step **904** of providing a single substrate **110** (such as a CMOS substrate), a step **908** of forming a temperature sensor **114** on a first portion **116** of the single substrate **110** for detecting temperature, a step **912** of forming a pressure sensor **120** on a second portion **122** of the single substrate **110** for detecting intracranial pressure, and a step **916** of forming an oxygen sensor **126** on a third portion **128** of the single substrate **110** for detecting oxygen concentration. In a preferred embodiment, steps **908**, **912** and **916** are parallel processes (CMOS processes), followed by post-processing steps such as to release the pressure sensor **120** and to deposit the platinum working electrode **410** over the top metal layer **142** of the oxygen sensor **126**. In particular, sensing portions **130**, **132**, **134** of the temperature sensor **114**, the pressure sensor **120** and the oxygen sensor **126**, respectively, are formed at different layers of the sensor device **100**. In an embodiment, the sensing portion **130** of the temperature sensor **114** is formed at the single substrate **110**, the sensing portion **132** of the pressure sensor **120** is formed at intra-metal layers **138** of the sensor device **100**, and the sensing portion **134** of the oxygen sensor **126** is formed at a top metal layer **142** of the sensor device. In this regard, forming the sensing portions **130**, **132**, **134** of the three sensors **114**, **120**, **126** at different layers of the sensor device **100** enables the three sensors **114**, **120**, **126** to be formed integrally on a single substrate **110** (i.e., integrated into a single chip) using a customized integrated fabrication flow. The steps in fabricating the integrated multimodal sensor device **100** will now be described in further detail according to an example embodiment of the present invention.

[0082] In the example embodiment, the integrated multimodal sensor device **100** is manufactured based on CMOS fabrication process using a 0.18 μm technology of GLOBALFOUNDRIES INC. As a first step, a single piece of blank wafer/substrate (preferably, silicon substrate) **110** is provided as illustrated in FIG. **10**A on which the temperature sensor **114**, the pressure sensor **120**, the oxygen sensor **126** and the associated ASIC **500** are to be formed. A thin layer of gate oxide is deposited to form the NMOS transistors for the temperature sensor **114**, oxygen sensor **126** and the ASIC **500**, and a polysilicon layer **1004** is formed and patterned as shown in FIG. **10**A. Subsequently, as shown in FIG. **10**B, an oxide layer **1006** is deposited on the substrate **110** and then patterned at portions **1008** where n+ dopants should be diffused or implanted. FIG. **10**B. Then, as shown in FIG. **10**C, the n+ regions **1010** of the transistors are formed in the substrate **110** and the oxide layer **1006** is removed. Subsequently, the ILD (interlayer dielectric) **1012** is deposited on the substrate **110** and patterned as shown in FIG. **10**D, and the VIA1 **1014** is deposited and subjected to CMP (chemical mechanical planarization) as shown in FIG. **10**E. The METAL1 (M1) layer **1016** is then deposited on the ILD layer **1012** and patterned as shown in FIG. **10**F.

[0083] Subsequently, the IMD**1** (intra-metal dielectric) layer **1018** is deposited over the METAL1 layer **1016** and ILD layer **1012** and patterned as shown in FIG. **10**G, and the VIA**12** **1020** is deposited and subjected to CMP as shown in FIG. **10**H. Then, the METAL2 layer **1022** is deposited over the IMD**1** layer **1018** and patterned as shown in FIG. **10**I. This metal layer **1022** will be utilised to define the bottom/stationary electrode **322** of the pressure sensor **120**. Subsequently, the IMD**2** (intra metal dielectric) layer **1024** is deposited over the METAL2 layer **1022** and the IMD**1** layer **1018** and patterned as shown in FIG. **10**J, and the VIA**23** **1026** is deposited and subjected to CMP as shown in FIG. **10**K. The METAL3 layer **1028** is then deposited on the IMD**2** layer **1024** and patterned as shown in FIG. **10**L. This metal layer **1028** will be utilised to define the release layer of the pressure sensor **120** (i.e., to form the cavity **350** as shown in FIG. **3**A). Subsequently, the IMD**3** **1030** is deposited over the METAL3 layer **1028** and patterned as shown in FIG. **10**M, and then the VIA**34** **1032** is deposited and subjected to CMP as shown in FIG. **10**N. The METAL4 layer **1034** is then deposited on the IMD**3** layer **1030** and patterned as shown in FIG. **10**O. This metal layer **1034** will be utilised to define the top/movable electrode **318** of the pressure sensor **120**. Subsequently, the IMD**4** layer **1036** is deposited on the METAL4 layer **1034** and patterned as shown in FIG. **10**P, and then the VIA**45** **1038** is deposited and subjected to CMP as shown in FIG. **10**Q. The METAL5 layer **1040** is then deposited on the IMD**4** layer **1036** and patterned as shown in FIG. **10**R. This metal layer **1040** will also be utilised to define the top/movable electrode **318** of the pressure sensor **120**, connected in parallel with the METAL4 layer **1034**.

[0084] Subsequently, the IMD**5** layer **1042** is deposited on the METAL5 layer **1040** and patterned as shown in FIG. **10**S, and then the VIA**56** **1044** is deposited and subjected to CMP as shown in FIG. **10**T. The METAL6 layer **1046** (i.e., the top metal layer **142**) is then deposited on the IMD**5** layer **1042** and patterned as shown in FIG. **10**U. This metal layer **1046** will be utilised to fabricate the electrodes **410** of the oxygen sensor **126**. Subsequently, a passivation oxide layer **1048** is deposited over the device and patterned as shown in FIG. **10**V. It will be appreciated that routing to/from and within the ASIC **500** can be done using any metal layer described above.

[0085] The CMOS wafer is now completed and the CMOS post-fabrication process will now be described. In order to ensure the CMOS compatibility, only low temperature post-process is used in the example embodiment. At this stage, the CMOS wafer have integrated thereon the temperature sensor **114**, the pressure sensor **120** (but the membrane not yet released), and the oxygen sensor **120** (but without the platinum working electrode **410** deposited yet). In the post-fabrication process, a first step is to etch the sacrificial stacked layer **1050** in order to release the suspended membrane **1052** as shown in FIG. **10**W. In order to etch the stacked metal (>99% Aluminium) and via (Tungsten) layers, a H2SO4+H2O2 solution is used to perform the release. During the etching of the sacrificial layer **1050**, the dielectric acts as stopping layer protecting top electrode **1040** and bottom electrode **1022**, electrical connections and IC, if required. After the release of the membrane **1052**, low stress oxide layer **1054** is deposited in order to seal the etching holes **1056** as shown in FIG. **10**X. The etching holes **1056** are sealed under a vacuum chamber, so the cavity **350** under the membrane **1052** is nearly in vacuum (about 6 mTorr). Subsequently, using photolithography and RIE the oxide layer **1054** is patterned in order to expose the oxygen sensor **126**, and then Platinum **1058** is deposited on the top metal layer **1046** and patterned using a lift-off process to form the working electrodes **410** as shown in FIG. **10**Y. In addition, using photolithography and RIE, the oxide layer **1054** is patterned in order to expose the pads (not shown in FIG. **10**Z) to allow electrical connections. Once the CMOS-MEMS fabrication is finished, biocompatible packaging process is performed, including deposition and patterning of a protective polymer coating material (preferably Parylene) **1060** over the pressure sensor **120** and deposition of a polymer (preferably, hydrogel (NAFION)) **1062** to encapsulate the oxygen sensor **125** as shown in FIG. **10**Z.

[0086] FIG. **11** illustrates an example completed sensor device (or sensor chip) **100** fabricated according to the example embodiment of the present invention.

[0087] An embodiment of the present invention will now be described where the sensor device **100** is packaged for in-vivo application as illustrated in FIG. **12**A and FIG. **12**B. In particular, there is provided an integrated multimodal sensor system **1200** for intracranial neuromonitoring as schematically depicted in FIG. **12**A incorporating the sensor device **100**. The sensor system **1200** comprises a flexible catheter **1210**, a flexible substrate **1214**, a sensor device **100** disposed on the flexible substrate **1214** and within a sensing end portion **1222** of the flexible catheter **1210**, and a guide tip member **1226** extending from the sensing end portion **1222** of the flexible catheter **1210** to facilitate penetration and directional guidance of the flexible catheter **1210** during insertion of the sensing end portion **1222** of the flexible catheter **1210** into the skull/cranium **1310** of a subject **1314** as illustrated in FIG. **13**. In the example embodiment, the sensor device **100** is glued onto a flexible substrate **1214** (e.g., flexible PCB) which is biocompatible. The soft nature of the flexible substrate **1214** minimises the possibility of disrupting the tissue, but it has been found to suffer from directional guidance. Accordingly, in the example embodiment, the guide tip member **1226** is assembled adjacent the sensor device **100** to provide facilitate penetration and directional guidance of the flexible catheter **1210** into the skull **1310**. Preferably, the guide tip member **1226** has a rounded tip and is made of silicone.

[0088] In the example embodiment, the sensor system **1200** further comprises a housing **1230** including a wireless communication module **1234** for receiving sensed data from the sensor device **100** and an antenna module **1236** for transmitting the sensed data wirelessly to one or more remote extracranial devices (e.g., a computer which receives the transmitted data and stores and/or displays the received data). The housing **1230** may further comprise a power source **1238**, such as a battery, for powering the sensor system **1200**. The power source **1238** and the wireless communication module **1234** are installed on a PCB **1240** of the housing **1230**. As illustrated in FIG. **12**A, the flexible catheter **1218** has a power wire **1242** and a signal wire **1246** therein each extending between and connected to the sensor device **100** and the housing **1230** (i.e., the PCB **1240**). The power wire **1242** is arranged to supply power from the power source **1238** to the sensor device **100** and the signal wire **1246** is arranged to transmit the sensed data from the sensor device **100** to the wireless communication module **1234**. In this regard, the sensor device **100** comprises a plurality of contacts **128** (or I/O ports) which is configured to be bonded to the power wire **1242** and the signal wire **1246** in the sensor system **1200**. FIG.

12C illustrates the same sensor device **100** as FIG. 1B but the power wire **1242** and signal wire(s) **1246** connected to the contacts **128** via bonding wires (only one bonding wire is shown in FIG. **12**C). By way of example only, there are 8 contacts **128** for connecting to 8 bonding wires. As can be appreciated from FIG. **11**, the contacts **128** are advantageously arranged so as to allow single-side wirebonding.

[0089] The sensor system **1200** also comprises a fastener (e.g., bolt) **1250** formed on a bottom side of the housing **1230** for attaching the housing **1230** to the skull **1210** of the subject **1214**, and thus supporting the flexible catheter **1210** and the sensor device **100** within the skull **1210** for intracranial neuromonitoring. As shown in FIG. **11**A, the flexible catheter **1210** attached to and extending from the housing **1230** may run through a central hollow portion of the fastener **1250**.

[0090] By way of example only, FIG. **12**B illustrates a prototype of the flexible catheter **1210** with the sensor device **100** embedded therein, along with the guide tip member **1226** extending from the sensor device **100**.

[0091] An overview of a method **1400** of fabricating the sensor system **1200** for intracranial neuromonitoring will now be described according to an embodiment of the present invention with reference to FIG. **14**. The method **1400** comprises a step **1404** of providing a flexible catheter **1210**, a step **1408** of providing a flexible substrate **1214**, a step **1412** of disposing a sensor device **100** on the flexible substrate **1214** and within a sensing end portion **1222** of the flexible catheter **1210**, and a step **1416** of forming a guide tip member **1226** extending from the sensing end portion **1222** of the flexible catheter **1210** to facilitate penetration and directional guidance of the flexible catheter **1210** during insertion of the sensing end portion **1222** of the flexible catheter **1210** into the cranium **1310** of a subject **1314**.

[0092] An overview of a method **1500** of intracranial neuromonitoring using the integrated multimodal sensor system for in-vivo application will now be generally described with reference to FIG. **15**. The method **1500** comprises a step **1504** of inserting the sensing end portion **1222** of the flexible catheter **1210** of the integrated multimodal sensor system **1200** into a cranium **1310** of a subject **1314** and a step **1508** of obtaining sensed data from the sensor device **100** of the integrated multimodal sensor system **1200**, the sensed data comprising temperature data, intracranial pressure data, and oxygen sensor data.

[0093] Accordingly, example embodiments of the present invention described herein provide a monolithically integrated multimodal sensor device **100** for intracranial neuromonitoring, including a temperature sensor for detecting intracranial temperature, a pressure sensor for detecting intracranial pressure, and an oxygen sensor for detecting oxygen concentration. In particular, the temperature sensor, the pressure sensor, and the oxygen sensor are integrated on a single substrate. This advantageously enables the sensor device having intracranial temperature, intracranial pressure and oxygen concentration sensing capabilities to be provided with a single catheter, thus eliminating the need to provide multiple catheters for obtaining multiple physiologic parameters. In addition, the sensor device **100** can advantageously be fabricated in a CMOS-compatible process, thus reducing fabrication costs. The miniaturized size of the sensor device facilitates the integration of full intracranial neuromonitoring system **1200** in a single catheter **1210**. As a result, the size of the bolt or burr hole required to perform intracranial neuromonitoring can be minimised, thus making it less susceptible to bleeding and infection. The overall intracranial neuromonitoring process is also greatly simplified since, for example, less catheters are involved.

[0094] It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

1. A monolithically integrated multimodal sensor device for intracranial neuromonitoring, the sensor device comprising:

a single substrate;

a temperature sensor formed on a first portion of the single substrate for detecting temperature;

a pressure sensor formed on a second portion of the single substrate for detecting intracranial pressure; and

an oxygen sensor formed on a third portion of the single substrate for detecting oxygen concentration,

wherein sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device.

2. The sensor device according to claim **1**, wherein the sensing portion of the temperature sensor is formed at the single substrate, the sensing portion of the pressure sensor is formed at intra-metal layers of the sensor device, and the sensing portion of the oxygen sensor is formed at a top metal layer of the sensor device.

3. The sensor device according to claim **1**, wherein the temperature sensor comprises one or more transistors, and the sensing portion of the temperature sensor includes an active region of the respective one or more transistors.

4. The sensor device according to claim **3**, wherein the transistor is a parasitic vertical PNP transistor.

5. The sensor device according to claim **1**, wherein the pressure sensor comprises one or more capacitive MEMS pressure sensors, and the sensing portion of the pressure sensor includes a movable electrode of the respective one or more capacitive MEMS pressure sensors.

6. The sensor device according to claim **1**, wherein the oxygen sensor comprises a switchable array of oxygen sensor elements, and the sensing portion of the oxygen sensor comprises a working electrode of the respective oxygen sensor elements.

7. The sensor device according to claim **6**, wherein the oxygen sensor is configured to switch to one of the oxygen sensor elements to provide the oxygen level reading which satisfies a predetermined sensitivity level.

8. The sensor device according to claim **1**, further comprises one or more application-specific integrated circuits formed on the single substrate for processing readings from the temperature sensor, the oxygen sensor, and the oxygen sensor.

9. A method of fabricating a monolithically integrated multimodal sensor device for intracranial neuromonitoring, the method comprising:

providing a single substrate;

forming a temperature sensor on a first portion of the single substrate for detecting temperature;

forming a pressure sensor on a second portion of the single substrate for detecting intracranial pressure; and

forming an oxygen sensor on a third portion of the single substrate for detecting oxygen concentration, wherein sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device.

10. The method according to claim **9**, wherein the sensing portion of the temperature sensor is formed at the single substrate, the sensing portion of the pressure sensor is formed at intra-metal layers of the sensor device, and the sensing portion of the oxygen sensor is formed at a top metal layer of the sensor device.

11. The method according to claim **9**, wherein the temperature sensor comprises one or more transistors, and the sensing portion of the temperature sensor includes an active region of the respective one or more transistors.

12. The method according to claim **11**, wherein the transistor is a parasitic vertical PNP transistor.

13. The method according to claim **9**, wherein the pressure sensor comprises one or more capacitive MEMS pressure sensors, and the sensing portion of the pressure sensor includes a movable electrode of the respective one or more capacitive MEMS pressure sensors.

14. The method according to claim **9**, wherein the oxygen sensor comprises a switchable array of oxygen sensor elements, and the sensing portion of the oxygen sensor comprises a working electrode of the respective oxygen sensor elements.

15. The method according to claim **14**, wherein the oxygen sensor is configured to switch to one of the oxygen sensor elements to provide the oxygen level reading which satisfies a predetermined sensitivity level.

16. The method according to claim **9**, further comprises forming one or more application-specific integrated circuits on the single substrate for processing readings from the temperature sensor, the oxygen sensor, and the oxygen sensor.

17. An integrated multimodal sensor system for intracranial neuromonitoring, the sensor system comprising:

a flexible catheter;

a flexible substrate;

a monolithically integrated multimodal sensor device for intracranial neuromonitoring, the sensor device comprising:

a single substrate;

a temperature sensor formed on a first portion of the single substrate for detecting temperature;

a pressure sensor formed on a second portion of the single substrate for detecting intracranial pressure; and

an oxygen sensor formed on a third portion of the single substrate for detecting oxygen concentration,

wherein sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device, wherein the monolithically integrated multimodal sensor device is disposed on the flexible substrate and within a sensing end portion of the flexible catheter; and

a guide tip member extending from the sensing end portion of the flexible catheter to facilitate penetration and directional guidance of the flexible catheter during insertion of the sensing end portion of the flexible catheter into the cranium.

18. The integrated multimodal sensor system according to claim **17**, wherein the guide tip member has a rounded tip and is made of silicone.

19. The integrated multimodal sensor system according to claim **18**, further comprising a housing including therein a wireless communication module for receiving sensed data from the sensor device and an antenna for transmitting the sensed data wirelessly to one or more remote extracranial devices.

20. A method of forming an integrated multimodal sensor system for intracranial neuromonitoring, the method comprising:

providing a flexible catheter;

providing a flexible substrate;

disposing a monolithically integrated multimodal sensor device for intracranial neuromonitoring on the flexible substrate and within a sensing end portion of the flexible catheter, wherein the sensor device comprises:

a single substrate;

a temperature sensor formed on a first portion of the single substrate for detecting temperature;

a pressure sensor formed on a second portion of the single substrate for detecting intracranial pressure; and

an oxygen sensor formed on a third portion of the single substrate for detecting oxygen concentration,

wherein sensing portions of the temperature sensor, the oxygen sensor and the pressure sensor, respectively, are formed at different layers of the sensor device; and

forming a guide tip member extending from the sensing end portion of the flexible catheter to facilitate penetration and directional guidance of the flexible catheter during insertion of the sensing end portion of the flexible catheter into the cranium.

* * * * *

patsnap

专利名称(译)	用于颅内神经监测的集成多模式传感器装置		
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[标]申请(专利权)人(译)	新加坡科技研究局 新加坡保健服务集团有限公司		
申请(专利权)人(译)	机构科学，技术和研究 新加坡保健PTE. LTD.		
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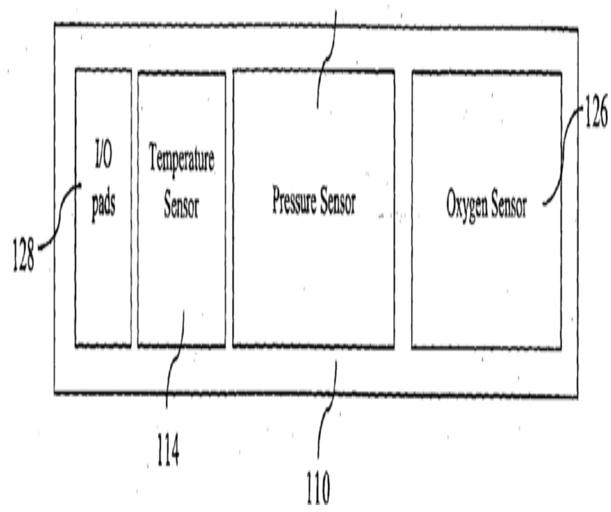
其他公开文献	US10463304		
外部链接	Espacenet USPTO		

摘要(译)

提供了一种用于颅内神经监测的单片集成多模式传感器装置，该传感器装置包括：单个基板;温度传感器，形成在单个基板的第一部分上，用于检测温度;压力传感器，形成在单个基板的第二部分上，用于检测颅内压;氧传感器形成在单个基板的第三部分上，用于检测氧浓度。特别地，分别感测温度传感器，氧传感器和压力传感器的部分形成在传感器装置的不同层处。还提供了一种集成的多模传感器系统，其包括传感器装置和相关的制造方法。


I/O pads
Temperature Sensor
Pressure Sensor
Oxygen Sensor
126
128
114
110