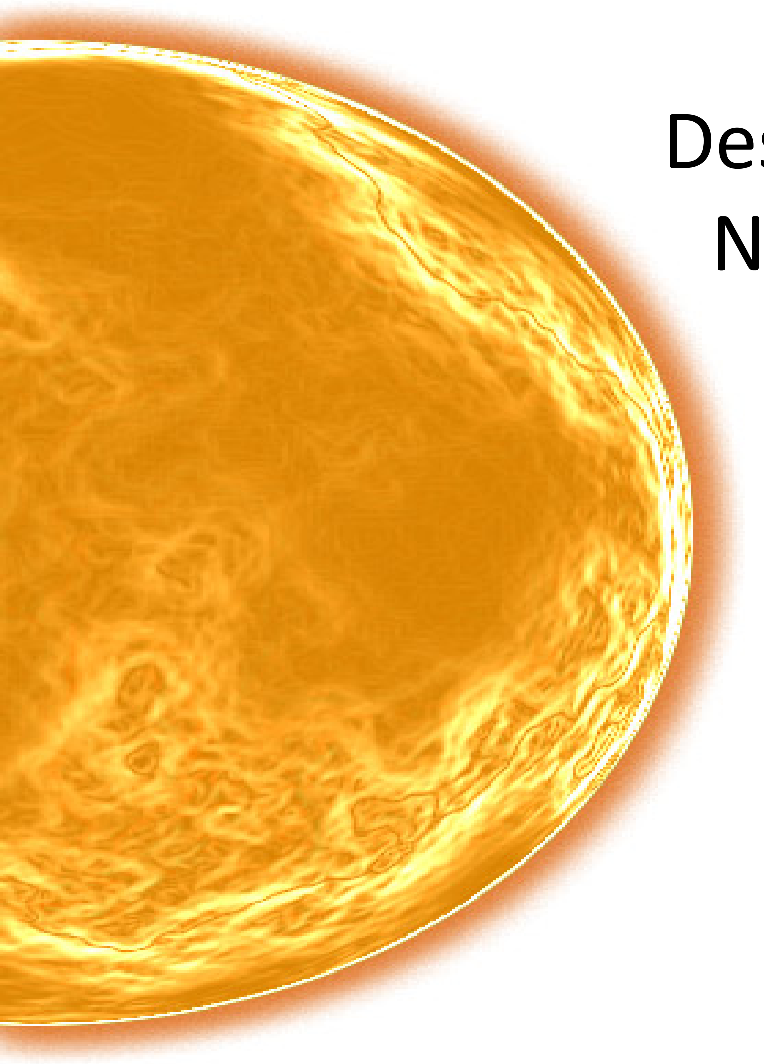

Design, Fabrication and Characterization of a Novel Piezoresistive Pressure Sensor for Blast Waves Monitoring

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Presenter's resume

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Thesis topic :

The objective of this thesis is to realize a complete wireless communication system, from the transducer to the reception system, allowing simultaneous wireless measurement of pressure signals from several sensors.

This system must have response times of less than a microsecond in order to properly restore the pressure peak and be able to measure its maximum overpressure. It should also be able to interrogate several sensors simultaneously without loss of information.

It includes finalizing the development of the complete following architecture:

This requires to develop a multiplexer system and to optimize the other blocs to make the full system working.

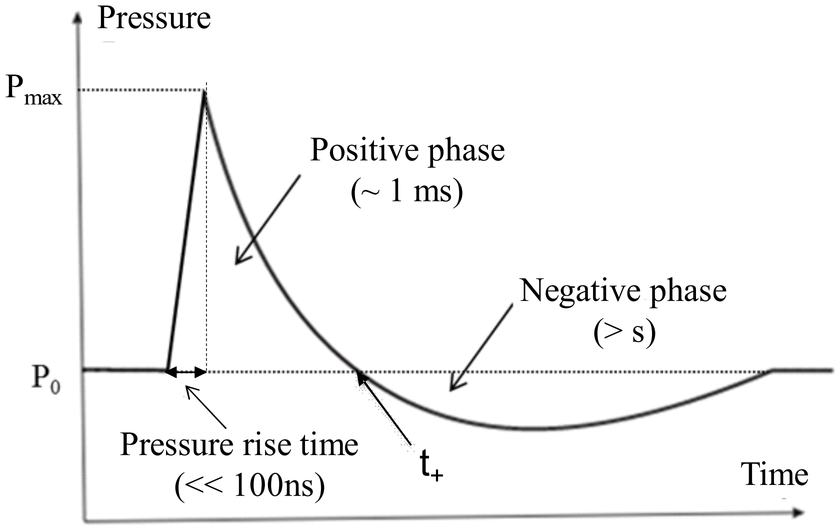
This characterisation led us to this article where we present the first transducer exploitable response.

Context

- Blast waves monitoring is required for many civilian and military applications, and especially for explosives characterization.
- Supersonic shock wave presents very fast shift of pressure (P_{max} of several bar/ ten of bar in t_{rise} < 10 ns)

- To analyse the effect of shock wave, the precise knowledge of P_{max} is mandatory
- Sensors with response time lower than 1 µs are required

- The piezoelectric transducers available on the market have a several microseconds response time



Typical theoretical pressure profile from a free field explosion

The article

We proposed a transducer using a miniature monocrystalline silicon membrane and silicon piezoresistive gauges.
The objective is to combine the advantage of miniature membrane (sensing diameter < 100 µm) and the high integration of electronic transduction.

This paper reports the design, fabrication and measurement results of this transducer, and explores the unexpected and undesirable mechanical response observed beyond 1 µs

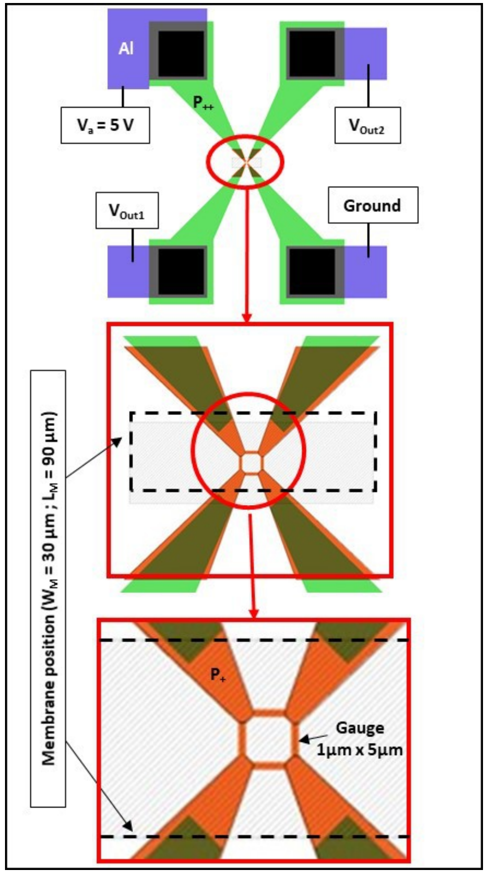
Transducer design

Membrane

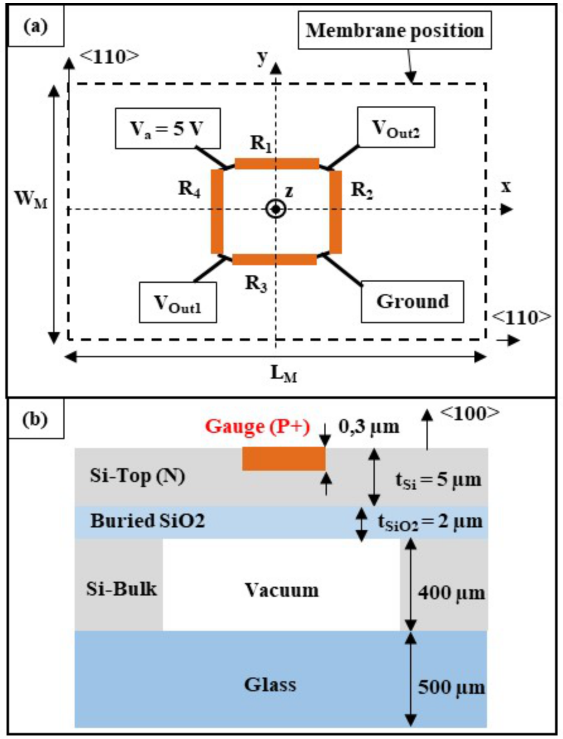
The transducer is a piezoresistive sensor based on a wheatstone bridge configuration.

For a constant pressure sensitivity, the lower membrane dimensions are, the bigger resonant frequency is. A study was made by J. Riondet [9] in order to find dimensions that offer the best compromise between resonant frequency and sensitivity.
The dimension of the gauges are dependent of the membrane dimensions.

A N-type monocrystalline 5µm-thick silicon membrane is used for the mechanical transducer. Rectangular shape membrane has targeted dimensions : W_M = 30 µm x L_M = 90 µm.



Top view of the mask used for the fabrication



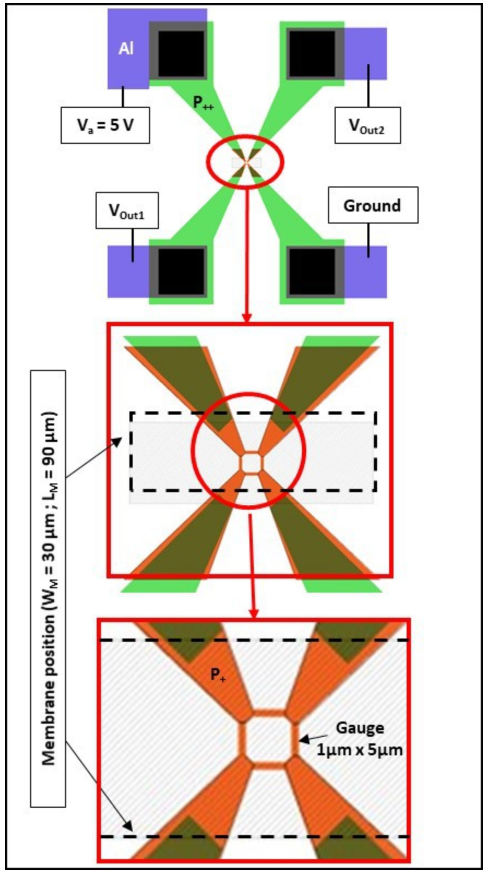
a) Top view of the Wheatstone bridge reported on the membrane surface, (b) Cross sectional diagram of the transducer

Gauges

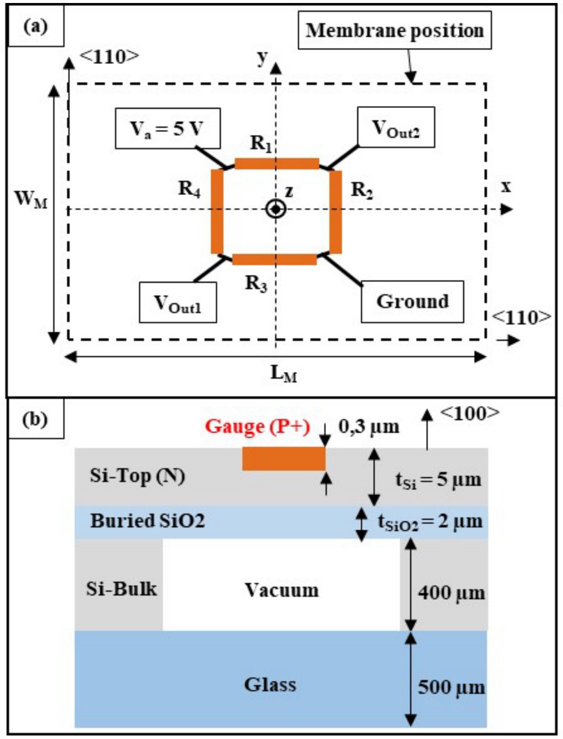
As for the membrane, a study was made to indentify the impact of the dimensions on both sensitivity and resonant frequency.
The smaller gauges are, the nearer it can be placed to the center of the membrane, increasing the constraints.

Here the dimensions were limited by technological restrictions. We worked with these constraints while optimizing the initial resistance of gauges.
We reduced the dimension of gauges and with dimensions in the order of micrometer we can have a resonant frequency in the order of ten of MHz. But dimensions could be reduced even more with process such as electronic lithography.

The electrical transducer is provided by P-type monocrystalline silicon gauges which are inserted at the center of the N-type silicon membrane.
Targeted gauges dimension is W_J = 1 µm x L_J = 5 µm.
To maximize the mechanical constraints in the gauges, their thickness (e_J = 0.3 µm) is low in front of the membrane's one.



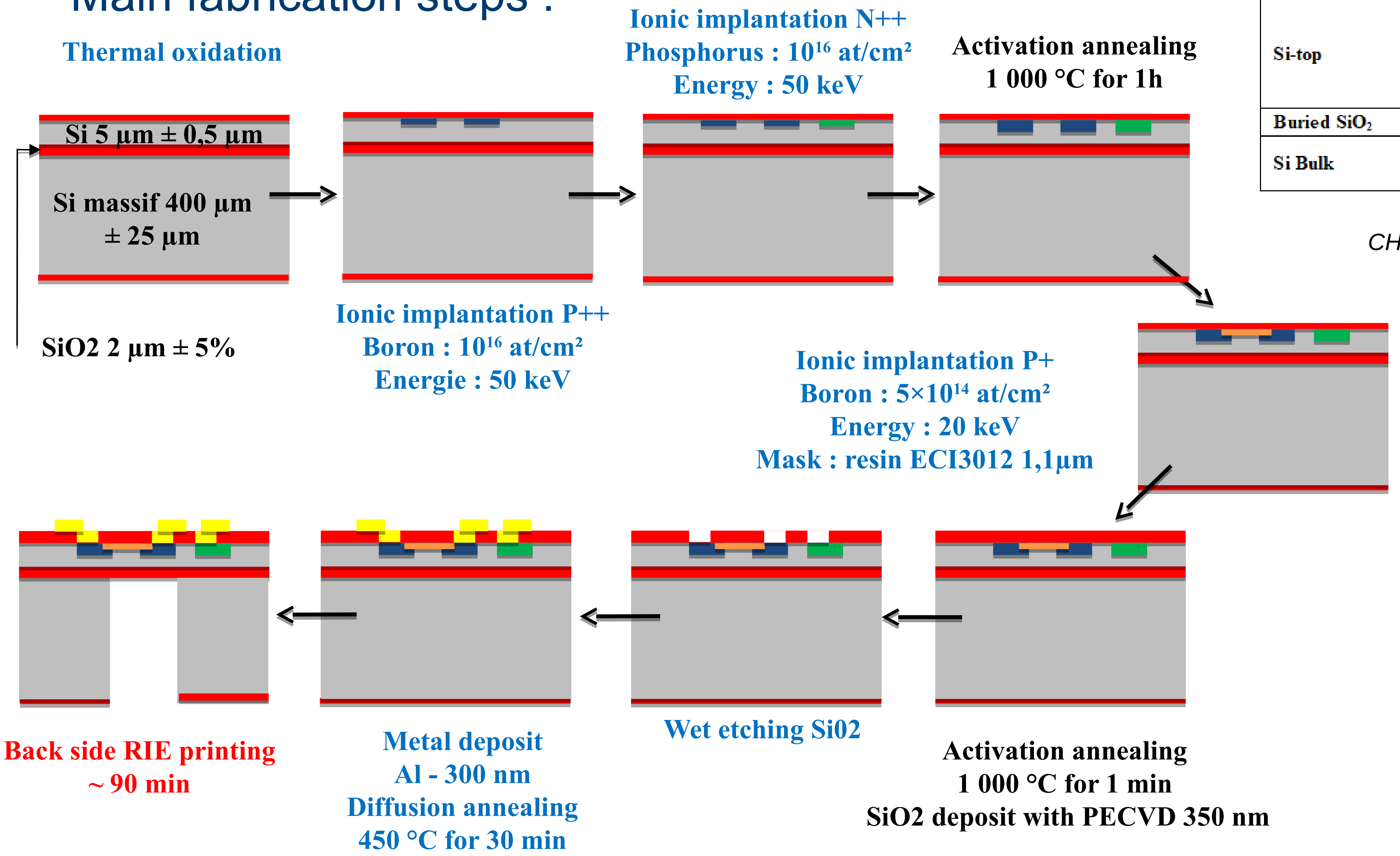
Top view of the mask used for the fabrication



*a) Top view of the Wheatstone bridge reported on the membrane surface,
(b) Cross sectional diagram of the transducer*

Transducer fabrication

Main fabrication steps :



Si-top	Orientation	(100)
	Type	N
	Doping level	$4.8*10^{15}$ to $1.6*10^{15}$ at/cm^3
	Thickness	(5.0 ± 0.5) µm
Buried SiO_2	Thickness	(2.0 ± 0.1) µm
Si Bulk	Orientation	(100)
	Thickness	(400 ± 15) µm

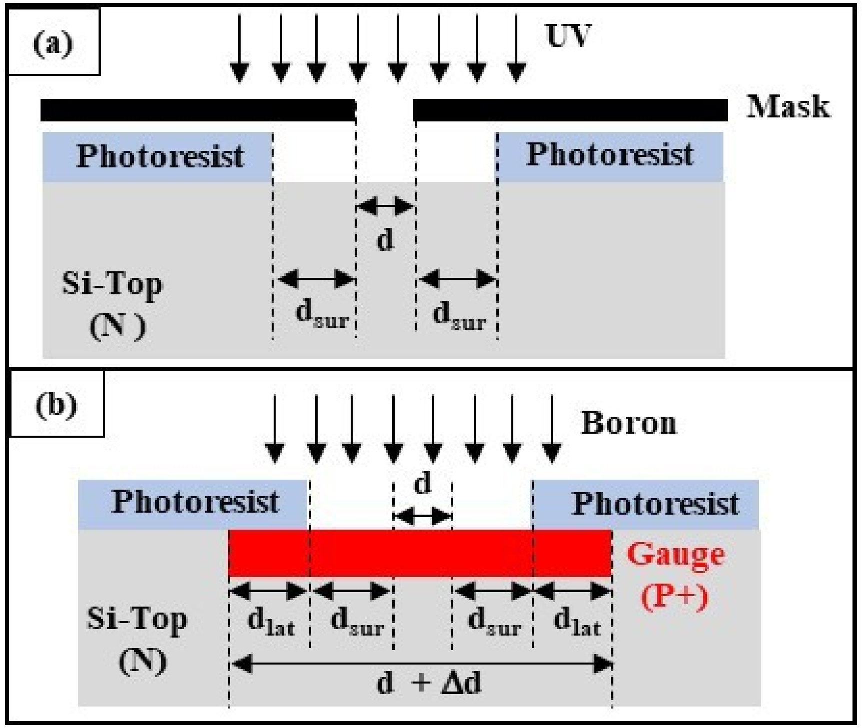
SOI WAFERS CHARACTERISTICS PROVIDED BY THE SUPPLIER

Electrical characteristics of the fabricated gauges

- R_{Transd} (between V_{out1} and V_{out2}) is of (2990 ± 100) Ω
(measured before the wafer dicing)
- Gauge resistance R_J is of 1380 Ω.
Theses two resistances differ because of the access resistance (mainly the P_+ interconnection between the gauges and the P_{++} interconnection).

Final dimensions of the gauges depend on d_{sur} and d_{lat} :
The final gauge width W_{Jf} and length L_{Jf} are respectively of 1.5 µm and 4.5 µm.
Given by :

$W_{Jf} = W_J + 2*d_{sur} + 2*d_{lat}$
$L_{Jf} = L_J - 2*d_{sur} - 2*d_{lat}$



Cross section diagram of gauge showing lateral dimension increase due to the (a) Photoresist etching and (b) Boron diffusion.

Membrane dimensions

The membrane width is higher than the mask opening.

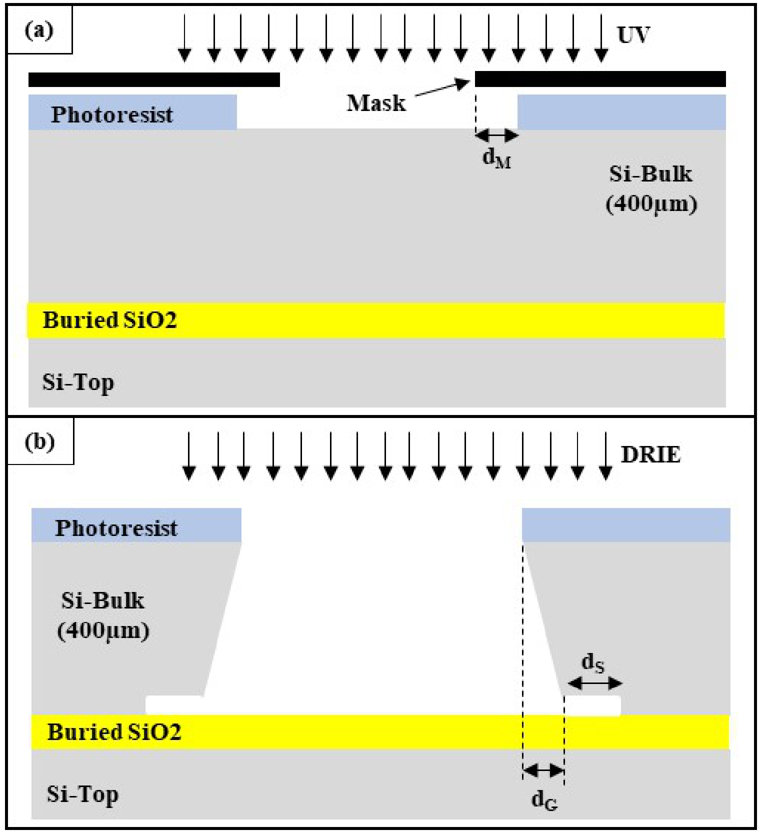
The dimensions of the fabricated membranes are measured on several samples using :
- Focus Ion Beam (FIB) etching for cross section realization
- Scanning Electron Microscopy (SEM) for dimensions measurements.

The results obtained are given in the following table :

Si-top thickness (µm)	5.0 ± 0.2 to 5.7 ± 0.2
Buried SiO_2 thickness (µm)	1.8 ±0.2 to 2.0 ±0.2
Membrane width (µm)	39.5 ± 0.2 to 42.5 ± 0.2

MEMBRANE DIMENSIONS MEASUMED by SEM

Si-top and buried SiO_2 measured thicknesses are in good agreement with the characteristics provided by the supplier.
Average membrane width is of 41 µm (37 % larger than the mask width, with a scattering of ± 3.6 %)



Cross section diagram of membrane showing lateral dimension increase due to the
(a) Photoresist etching and (b) Si DRIE etching.

Simulation results to static pressure

Comsol simulation

COMSOL simulations were performed to predict the static transducer performances.
The full design was considered with two membrane dimensions corresponding to the lowest and the highest mechanical stiffness given by the measured membrane dimensions. The static pressure sensitivity and the fundamental mechanical resonant frequency are reported in the following table :

COMSOL SIMULATED TRANSDUCER PERFORMANCES
Case-1: $t_{Si} = 4.8$ µm, $t_{SiO2} = 2$ µm, $W_M = 43$ µm, $L_M = 103$ µm
Case-2: $t_{Si} = 5.9$ µm, $t_{SiO2} = 2$ µm, $W_M = 39$ µm, $L_M = 99$ µm

	Case 1	**Case 2**
Static pressure sensitivity S_{Transd} (µV/V/bar)	209	138
Fundamental mechanical resonant frequency F_o (MHz)	25.7	34.3

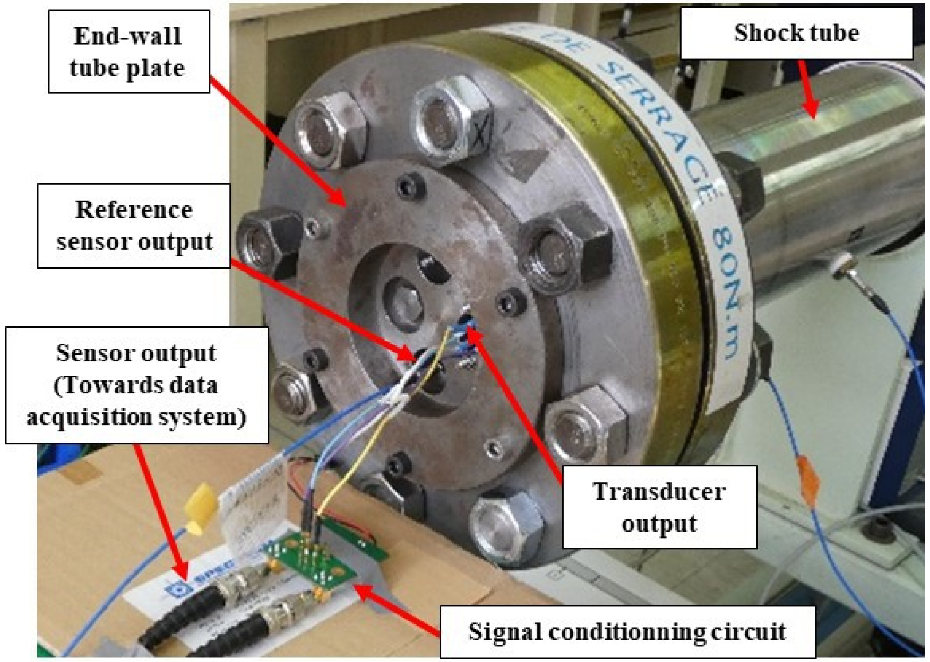
The simulated static pressure sensitivity is between 138 µV/V/bar and 209 µV/V/bar corresponding to an uncertainty of ± 20.5 %.
The simulated fundamental mechanical resonant frequency of the membrane is between 25.7 MHz and 34.3 MHz, corresponding to an uncertainty of ± 14.3 %.

Shock tube characterization of the fabricated sensor

Setup

A 2.7m-length and 11cm-diameter metrological shock tube allows generating a pressure step with a rise time lower than 10 ns.
The driver section is filled with nitrogen gas while the driven section is at atmospheric pressure.
The diaphragm which separates the two sections is a standard nickel rupture disc that opens fully and responds within milliseconds to applied overpressure. Its rupture creates a shock wave that propagates within the driven section until it reflects on the end-wall of the tube where the pressure is measured both by our transducer and a commercial reference sensor (PCB Piezotronics 134A24).

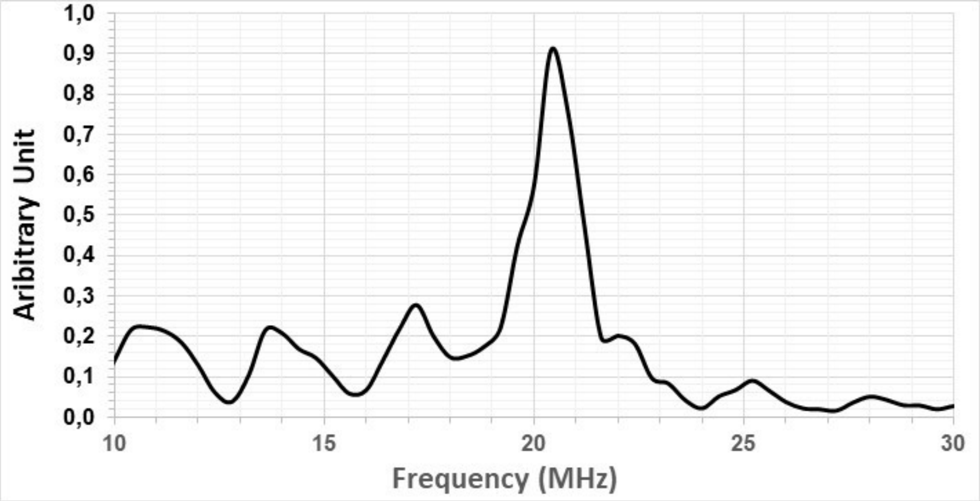
The transducer output is connected to a conditioning circuit via 10cm-length shielded wires. The static gain of this circuit is of 0.9 with a cut-of frequency of 35 MHz. The sampling frequency of the data acquisition system is of 100 MHz.



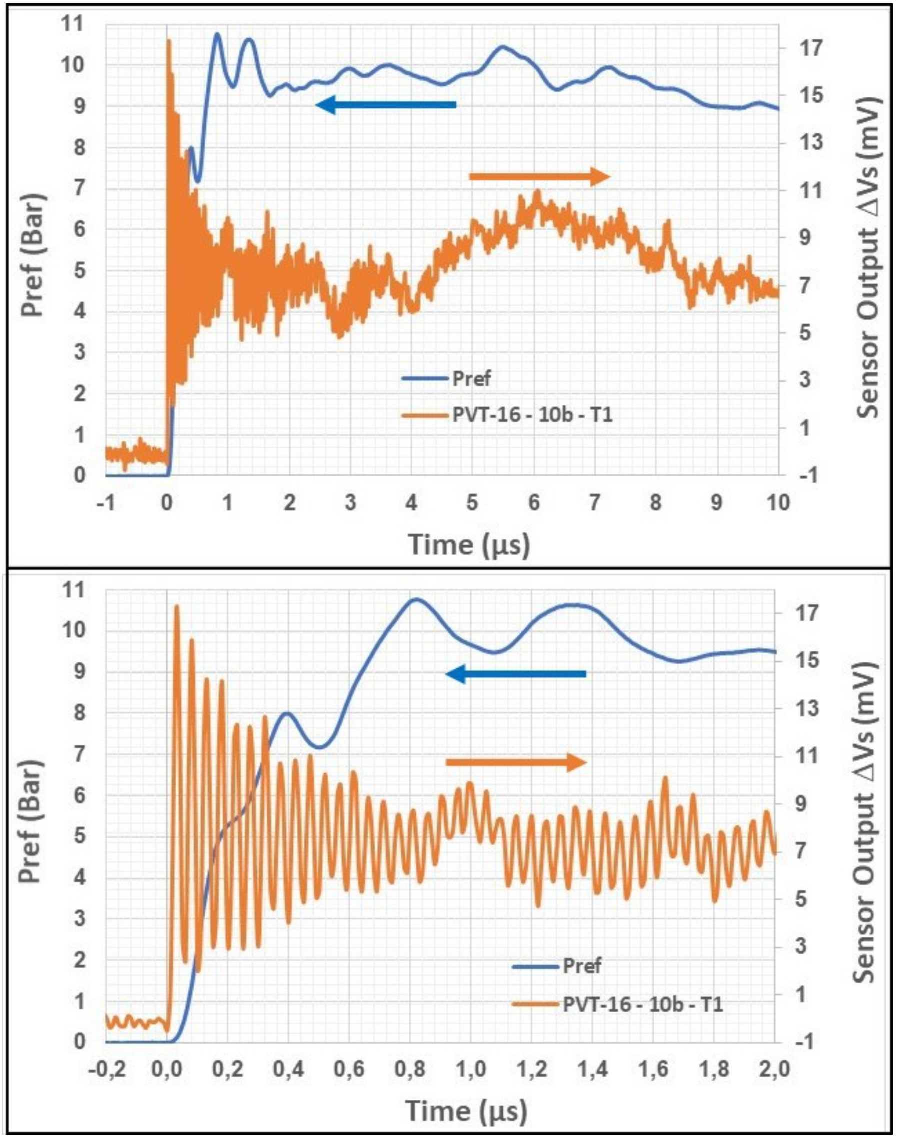
Sensor response to pressure step

The sensor response (at the output of the conditioning circuit) to a 10 bar pressure step is shown on the sensor response.
A typical damped oscillation is present in the first micro-second due to the excitation of the fundamental mechanical resonant mode of the membrane. From this measurement result, we can derive the transducer characteristics: a rise time of 30 ns, a response time lower than 1 µs and a steady-state pressure sensitivity around 200 µV/V/bar, assuming a gain of 0.9 from the conditioning circuit. This sensitivity is in good agreement with the predicted one.

The fundamental resonant frequency of 20.4 MHz is also in good agreement with the simulated one, as shown on the following spectral analysis :



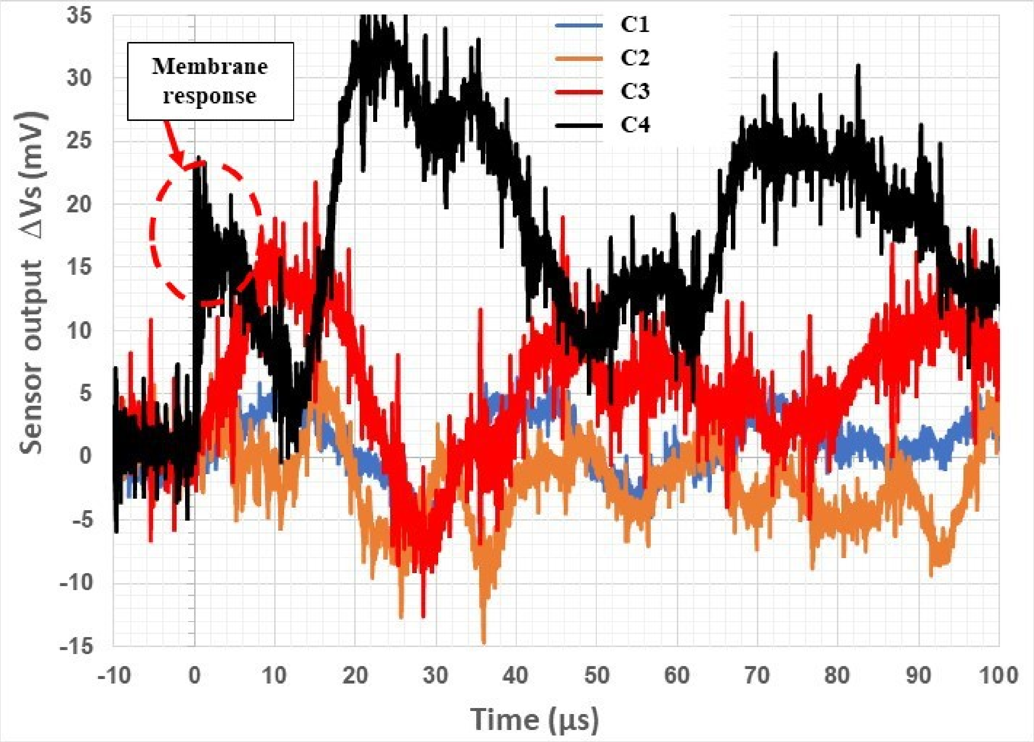
Spectral analysis of the sensor response



Sensor response to a 10 bar step pressure (orange line) and reference sensor (blue line)

Analysis of the observed sensor drift

Beyond 1 µs, we observe that an unexpected drift appears.
The following figure represents the sensor response to a 10 bar pressure step using four different configurations



Sensor output with a 10 bar pressure step for different measurement configurations.
Configuration C1: Without membrane - With Cover
Configuration C2: Without membrane - Without Cover
Configuration C3: With membrane - With Cover
Configuration C4: With membrane - Without Cover

Conclusions and future works

The characterization of supersonic shock wave produced by explosives requires sensor with response time lower than 1 µs. With sensing diameter above 900 µm, the commercial sensors are not able to fulfill this specification.

We propose a pressure transducer based on a miniature silicon membrane and piezoresistive gauges in order to combine the advantage of miniature sensing area and microelectronic integration.

In this communication, a miniature piezoresistive pressure sensor was designed, fabricated and characterized with a shock tube.
The transducer has a very low rise time (near to 30 ns) and a short response time (lower than 1 µs) thanks to the high fundamental mechanical resonant mode of the membrane (near to 20 MHz).

Mechanical parasitic effects, that leads to large drift after few microseconds, were explored and identified. This effect is attributed to the metallic holder deformation under shock wave. New packaging with higher mechanical stiffness will be designed in order to reduce these undesirable effects in the pressure response.

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