SAW Pressure Sensor for Vacuum Control Applications

P. Nicolay[1], O. Elmazria[1,3], F. Sarry[1] , L.Bouvot[1,] H. Kambara[2], K.J. Singh [1,*] and P. Alnot[1]
[1]LPMIA, UMR 7040 CNRS, Nancy University, 54506 Vandœuvre-lès-Nancy, France
[2]ADIXEN, ALCATEL Vacuum Technology France (AVTF), 74009 Annecy, France
[3]Ecole Supérieur des Sciences et Techniques d'Ingénieurs de Nancy, 54506 Vandœuvre-lès-Nancy, France

Corresponding author: omar.elmazria@lpmi.uhp-nancy.fr

***Abstract*— A new kind of surface acoustic wave (SAW) sensor has been developed in order to measure sub-atmospheric pressure below 100 mTorr with accuracy better than 0.1 mTorr. It provides an efficient measuring solution in a pressure range inaccessible in past by conventional diaphragm-based SAW sensors. Indeed, due to the small bending force in low pressure and limited sensitivity, diaphragm-based SAW sensors are only suited to monitor relatively high pressure with a precision hardly better than 0.5 Torr. In order to reach precision level better than 1 mTorr at sub-atmospheric pressure for vacuum technology applications, a radically different SAW-based solution is desired. Our device aims to measure sub-atmospheric pressure less than 100 mTorr with a threshold resolution better than 0.1 mTorr. The concept is similar to the one used by Pirani pressure gauges. However, it is claimed that a heated and suspended SAW device may have better sensitivity. A theoretical model based on the basic concepts of gas kinetic theory and thermodynamics is presented. The validity of the model is checked by comparison between theoretical and experimental results.**

Keywords- Vacuum; pressure sensor, SAW

I. INTRODUCTION

The development of MEMS solutions has contributed to the development of miniature pressure sensors based on various physical principles. For vacuum applications of our interest, many possible solutions have been investigated and some of them have already been commercialized. Capacitance, piezo-resistive strain, micro and nano Pirani gauges (etc…) are some of the examples [1-3].

Because the oscillation frequency of a SAW device is sensitive to applied stress and strain, SAW materials have also been used (for more than thirty years) to design miniature diaphragm-based pressure sensors. But, although very useful for monitoring relatively high pressure, these devices lack the ability to sense minute pressure changes with high precision in the low pressure range. The main reason for the observed limitations is that SAW sensitivity to stress and strain is not large enough to allow for detecting the very small bending variations which occurs in low pressure. And even if sensitivity and precision can actually be improved by various means (operating at higher frequencies, using sensitive cuts and thinner diaphragms with larger radius, implementing a number of design tricks…), the natural fragility of SAW materials seems to set a limit to precision improvement around 15 mTorr.

In this work, we propose an original SAW-based sensor using the working principle of thermal pressure gauges, for low pressure measurement and vacuum control applications. The behaviour of the sensor versus pressure is shown and analyzed. The sensitivity in low pressure appears very high and it is observed that sensitivity can be further improved with an optimal choice of operating frequency and SAW materials.

II. WORKING PRINCIPLE OF THE SENSOR

Conventional thermal pressure gauges utilize the pressure dependence of gas thermal conductivity to detect pressure changes when pressure is below a certain limit [4]. Sensor generally consists of a hot electrical wire. In the event of pressure change, more or less gas molecules come in contact with the wire. This causes the change in equilibrium temperature of the wire and therefore a change in its electrical resistance. Calibration of change in resistance versus pressure can then be used to measure gas pressure.

In contrast to conventional thermal pressure gauges (thermocouple, Pirani…), the sensitive element in our sensor is a heated and suspended SAW device. Heated and suspended SAW device may have the advantage over Pirani pressure sensor in terms of temperature sensitivity. Indeed, when the SAW material and its crystallographic cut are well chosen, the sensor exhibits high TCF value. This property makes it very sensitive to pressure variation. Moreover, sensitivity can be further improved by increasing the operating frequency of the device.

*On leave: Applied Physics Depart. Guru Nanak Dev University, Amritsar-143005, India

The behaviour of the sensor can be anticipated using the basic concepts of gas kinetic theory and thermodynamics. The average sensitivity in Knudsen regime can notably be calculated in a very simple way. The equilibrium temperature (T_{eq}) is reached when the power dissipated into the surrounding medium by radiation and gas conduction is equal to the power injected by the heating system into the device. A pressure change induces the variation of the power evacuated by gas conduction, which has to be compensated by an opposite variation of the power dissipated by radiation. This variation implies the evolution of the device temperature from T_{eq} to T_f (final equilibrium temperature). The temperature variation ΔT= T_{eq} - T_f can be easily expressed by the following equation [5,6]:

$$\Delta T = \sqrt[4]{\frac{\Psi(T_0 - T_{eq})\Delta P}{\varepsilon\sigma} + T_{eq}^4} - T_{eq} \qquad (1)$$

where ΔP is the pressure variation, T_0 is the gas temperature, ε is the emissivity of the considered body (substrate), σ is Stephan's constant and Ψ is given by the equation:

$$\Psi = \frac{3/2\,k}{\sqrt{2\pi \cdot mkT_0}} \qquad (2)$$

where k is the Boltzmann constant and m is the mass of one gas molecule.

The theoretical sensitivity per mTorr is obtained by multiplying the ΔT obtained for a pressure variation of 1 mTorr, by the TCF value of the considered substrate (75 ppm/°C in our case).

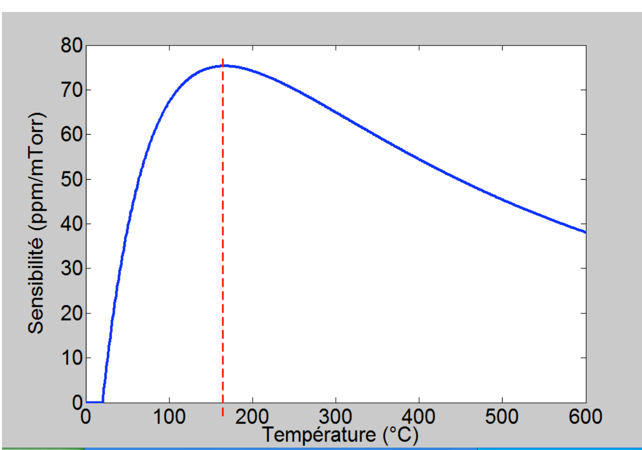

Fig. 1 : Theoretical sensitivity with respect to T_{eq} for a $LiNbO_3$ Y+ 41°−X heated SAW device plunged in air at room temperature (T_0 = 25 ° C) and at low pressure (Knudsen regime). The emissivity of LiNbO3 is taken equal to 0.75.

Figure 1 shows the theoretical sensitivity with respect to the initial equilibrium temperature, obtained from (1) for a $LiNbO_3$ $Y + 41°-X$ heated SAW device plunged in air at room temperature (T_0 = 25 °C). This figure also demonstrates that a maximum sensitivity as high as 70 ppm/mTorr can be expected if the operating temperature is set around 175 °C. Such a sensitivity would enable to discriminate pressure steps as small as 10^{-5} Torr once using a heated SAW device operating at 1GHz with a measurement accuracy of 1 kHz.

III. Experimental Set Up

The device consists of a basic SAW delay line surrounded by a printed platinum or gold thin film used as a heating resistor. Both structures are simultaneously deposited on a small piezoelectric dye. As shown in Figure 2, the SAW device under test is completely suspended with wire bonding (25 µm) in order to thermally insulate the whole piece from the rest of the experimental set-up. Interdigital transducers (IDTs) are connected to Printed Circuit Board (PCB), heater and RF equipment (via SMA connector) by wires. The number of wires varies depending on the maximum electric current needed for heating. Increasing the number of such wires make the system more robust but increase the thermal conduction between SAW device and PCB. RF signal is transmitted via PCB, coaxial connector and SMA (mounted on an electrical feed through) to the characterization equipment (NWA in our case). The heating power is also transmitted via the same electrical feed through, but through a DB9-type connector.

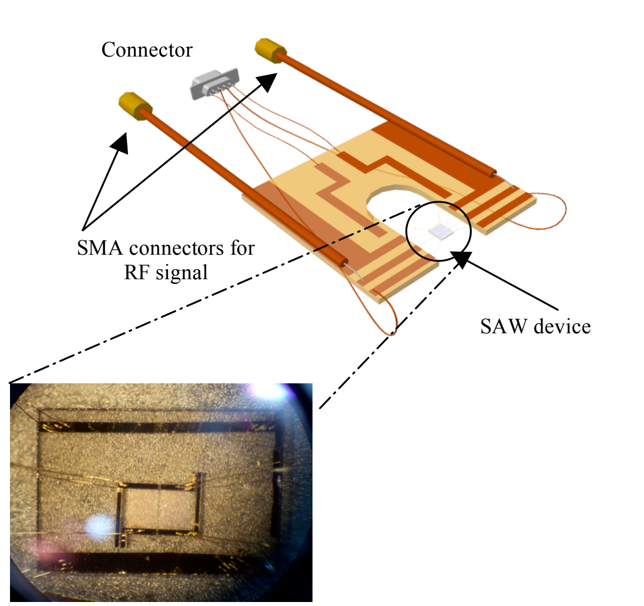

Fig. 2: detailed description of the SAW thermal sensor and packaging used for the experimental set-up. SAW device is connected via wire bounding to PCB.

The experimental results were obtained with a SAW delay line patterned on a $LiNbO_3$ Y+41 °− X substrate. The substrate dimensions were 7x5x0.3 mm^3. The operating frequency at room temperature was 244.7 MHz. Ti/Au inter-digital transducers were of single type, with uniform finger spacing. Spatial periodicity of IDT was fixed to λ=15 μm. The experimental points were obtained by frequency characterization (phase tracking) performed with a network analyzer HP8752A.

IV. Results and discussion

The measuring range of the sensor depends primarily on the physical principle used. Concerning thermal pressure gauges, this range is mainly governed by the evolution of the mean free path of gas molecules which respect to pressure. For conventional Pirani gauge, the measuring range is generally comprised between 10^{-4} to 10^{-2} Torr. To fully characterize our SAW sensor, we studied its behaviour in a wide pressure range, from 10^{-5} Torr to 1000 Torr. Figure 3 shows the variation of frequency of SAW sensor versus pressure (without any forced convection mechanism). For calibration, the pressure was measured by using two commercial capacitive gauges in order to completely cover the investigated pressure range. One can observe that there are three clearly identified regimes:

- Knudsen regime (low pressure) where the sensitivity is very high,
- A transition regime where the sensitivity tends to zero because the gas thermal conductivity reaches its limit value,
- A third regime where the sensitivity is low but not zero due to the sensitivity of the device to hydrostatic pressure and thanks to pressure dependant convective cooling.

Note that the sensitivity in transition regime can be improved by using forced convection or by extending the Knudsen regime toward high pressure. This extension can be achieved by adding a cover over the sensitive area of the sensor thereby defining a small chamber whose dimensions will stay below the mean free path of gas molecules until higher pressures are reached (i.e. extension of Knudsen regime). This solution has already been implemented for MEMS and NEMS Pirani gauges [7].

In order to demonstrate the high accuracy of our SAW thermal pressure gauge in low pressure, we performed measurements in the range 10^{-5} to 10^{-4} Torr (see figure 4). It can be observed that pressure steps as small as 0.1 mTorr can be easily discriminated and also that it should be possible to achieve a maximum accuracy of 0.01 mTorr with some improvements in the system. Indeed, a pressure change of 0.1 mTorr generates a frequency shift around 10 ppm (see figure 4). In our present design, this corresponds to a frequency shift of 2.4 kHz because the operating frequency is 244 MHz. If it is assumed that measurement accuracy of 1 kHz can be achieved with our testing equipment and that we can use a SAW device with an operating frequency raised to 1GHz, the accuracy of the sensor would be enhanced to 0.01 mTorr. Moreover, from Eq. (1), it can be observed that the sensitivity can also be increased by decreasing the emissivity value (ε). Such decrease could be achieved through the coating of the surface with a low-ε metal compound.

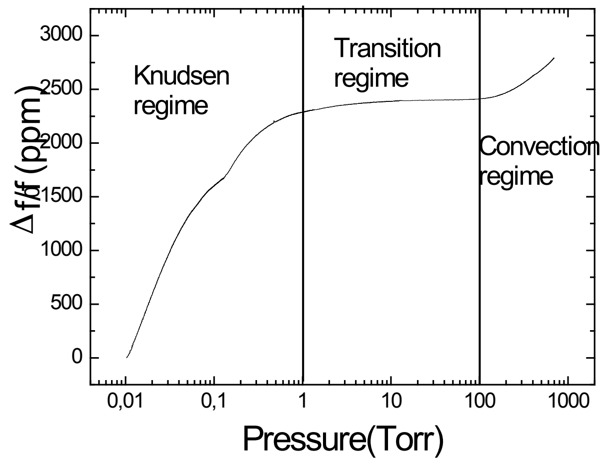

Fig. 3: SAW sensor response with respect to pressure. Identification off three distinct regimes.

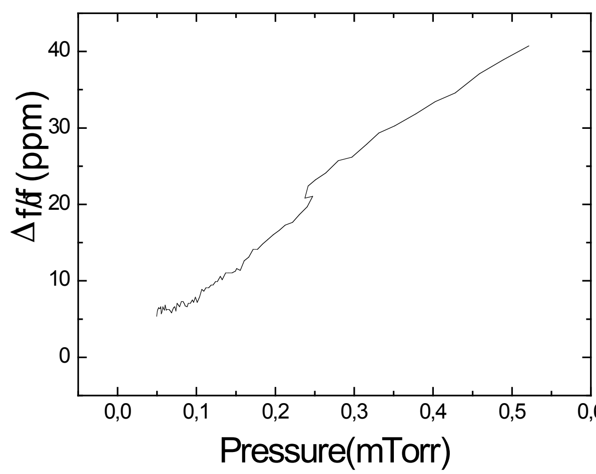

Fig. 4 : SAW-Pirani sensor response in the pressure range of 10^{-5} Torr to 10^{-4} Torr .

In Knudsen regime, sensor is most sensitive. In order to study the dynamic behaviour of the sensor in this regime and therefore determine its response time, a series of new measurements have been undertaken. The results are presented in Figure 5. In Figure 5-a, the response of the SAW-Pirani sensor for stepwise pressure variation is compared to the response of a capacitive gauge. It can be seen that the SAW thermal pressure sensor exhibits a quite high response time, which presents a disadvantage for applications requiring rapid response such as the deep etching process (DRIE) used in

MEMS technology. In order to find the theoretical limits of the sensor and ways to improve its performance, the theoretical response has been calculated by taking into consideration the characteristics of the device (type and size of the substrate, thermal capacity, TCF value, heating power and related equilibrium temperature) [6]. In figure 5-b, experimental dynamic response is compared to theoretical one. The agreement is quite good between the two curves. This validates the developed dynamic model and it is speculated that it provides realistic estimation for the sensor response time.

Although various solutions to improve the response time are currently under examination, response time is still the major drawback of the SAW thermal pressure sensor.

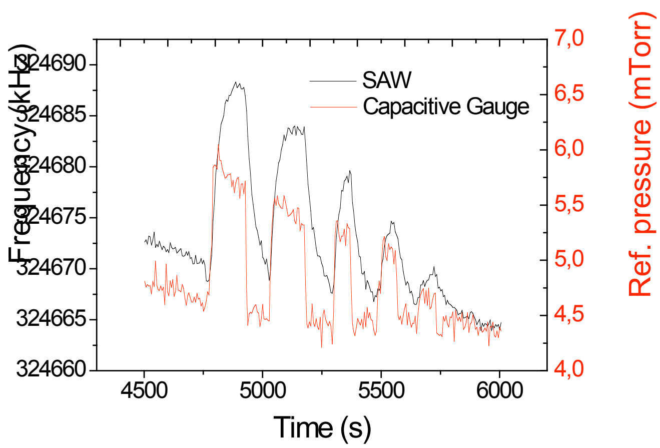

Fig. 5-a : Comparison of response time between capacitive gauge and our SAW thermal pressure sensor.

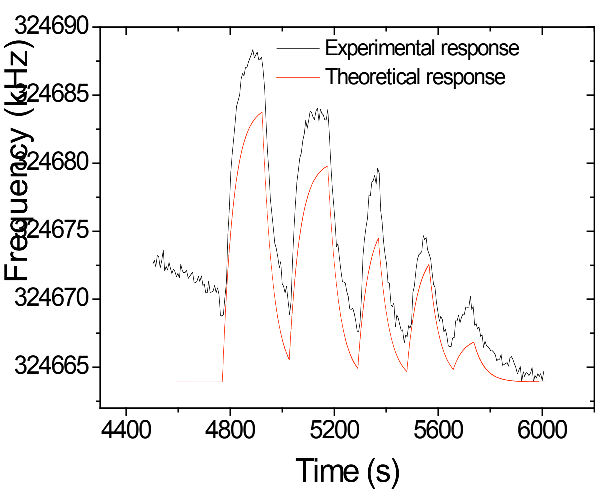

Fig. 5-b: Comparison of experimental and theoretical response time of the sensor

V. CONCLUSION AND PERSPECTIVES

The technical feasibility of SAW thermal pressure sensor for accurate pressure measurement in vacuum has been demonstrated. Current objective is to develop a commercial sensor. This requires systematic and wide pressure range studies of the performance of the sensor, which may include: limitation of sensitivity and accuracy in each sub-range of pressure (10^{-5} mbar to 1000 bar), incertitude, response time, drift, aging and reproducibility of measurements.

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