Electro-Thermal Modeling: Design Tool for the Conception of a Low Power SnO_2 Gas Sensor

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ABSTRACT

The sensor's operating principle consists in measuring the resistance variations of a thin semiconductive layer heated between 250 and 450°C as a function of the nature and quantity of the molecules adsorbed on its surface.

The reduction of the power consumption due to the heating of the sensitive layer, is one of the challenge for SnO_2 gas sensors. We propose a new solution using a silicon oxynitride membrane (SiO_xN_y) to reduce the electric power consumption, allowing a low power consumption (65 mW) at the operating temperature (450°C).

Using a commercially available electrothermal simulation software (SESES™) a new design has been determined.

A new sensors generation has been successfully fabricated and its mechanical strength and thermal performances have been correlated with FEM electro-thermal simulations.

Keywords: Gas Sensor, Micro Heater, Silicon Oxynitride Membrane, FEM Thermal Simulation

INTRODUCTION

The development of tin oxide integrated gas sensors using standard micro-electronics technologies [1-3] has a considerable growing interest due to their many advantages compared to thick film devices. These advantages mainly result from their low manufacturing cost, low power consumption and their ability to improve gas selectivity by developing sensors arrays and by incorporating, on the same chip, IC for data acquisition and signal processing.

These sensors operate at relatively high temperature (250 - 450°C) and the sensitive area should be thermally insulated from the remaining part of the sensor. This is why the sensitive layer is generally deposited on a thin membrane. Two main difficulties have thus to be overcome simultaneously: the membrane should exhibit a low thermal conductivity in order to achieve low power consumption and should exhibit good mechanical strength leading to a high fabrication yield.

The silicon membrane usually employed due to its mechanical properties, leads to power consuming devices (>100mW) and has to be replaced by a dielectric membrane. Even if silicon dioxide (1.4 W/m.K.) seems to be the best membrane material, it presents a high residual stress level giving rise to mechanical strength problem and weak fabrication yield.

Two solutions using dielectric materials are generally proposed in the literature: either stacked membranes using compensating layers of compressive (oxide) and tensile (nitride) stress to adjust the residual stress [4-6] or non stoechiometric nitride (SiN_X) membrane [7-9].

After a short reminder of the silicon membrane device properties, we propose, in this paper, a new solution using a silicon oxynitride (SiO_XN_y) membrane obtained in a single process step.

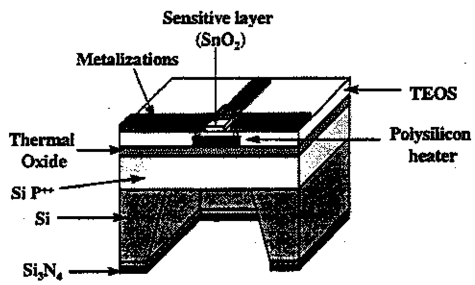
GENERAL FEATURES OF THE SnO_2 GAS SENSOR WITH A SILICON MEMBRANE

The device is schematically depicted in Figure 1 : the sensitive layer (SnO_2) is deposited on a heating element, consisting of a polysilicon resistor with Pt/Ti/Cr contacts. Electrical insulation makes use of a silicon dioxide, and the p++ doped Si layer provides mechanical support, while its low thickness allows for a relatively good thermal insulation. The p++ silicon membrane is obtained by anisotropic KOH etching from the back-side of the wafer.

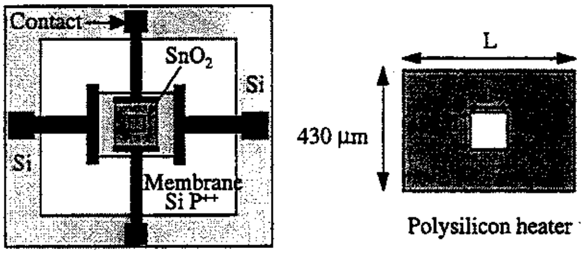
The thickness of the silicon membrane greatly impacts the manufacturing yield after KOH etching: for a 1.5 µm thick membrane, the yield after dicing, bonding and assembly is less than 40% and may cause breakdown problems while operating. It has been shown experimentally that the thickness of the silicon membrane must be kept between 2 and 3 µm in order to reach acceptable values of fabrication yield (>90%). These thickness values greatly increase the power consumption, as thermal loss by conduction increases with the increasing membrane thickness.

The design of the heater and the size of the membrane have been optimized using a FEM simulator SESES. The thermal performances of the optimized sensor are given on Table 1.

It turns out from these results that the temperature homogeneity over the sensitive layer is quite good (temperature of 90% of the total available area is between 450 and 410°C) and that the polysilicon/metal contacts are kept below 300°C avoiding thus electro-migration and interdiffusion problems.



(a)



(b)

Fig.1. Schematic view of the chemical sensor (a) general view (b) top view

Table 1. Comparison of the experimental measurements with the simulations of the thermal performance of the silicon membrane sensor

	Experiment	Simulation
Maximum Temp. (°C)	450	450
Power consumption (mW)	200	200
Average Temp. on the sensitive area (°C)	430	430
Polysilicon Contact Temp (°C)	290	297

OPTIMIZATION OF LOW POWER SnO_2 GAS SENSOR WITH AN OXYNITRIDE SUPPORTING MEMBRANE

The general structure is the same as presented on Figure 1 excepted that the Silicon membrane has to be replaced by the silicon oxynitride membrane.

SiO_xN_y membrane properties

The Silicon oxynitride composition has been adjusted to the optimum value Si $O_{0.89}$ $N_{0.73}$ in order to have a low residual stress. It has been shown that good fabrication yield (above 95%) are obtained for membrane thickness ranging between 1.0 and 2.0 µm and the optimum value has been fixed to 1.5 µm.

The thermal conductivity of the silicon oxynitride membrane has been evaluated by fitting the simulated results to the measured values of the device features (power consumption, average temperature over the sensitive layer and contact temperature). As it will be shown later, a good agreement is obtained for a thermal conductivity of 5W/m.K. This value is slightly lower than that of nitride and confirms that silicon oxynitride is a good candidate for thermally insulating membranes.

Optimization of sensor design using FEM simulations

The optimization of the sensor structure has been done using a commercially available coupled electrothermal simulation software (SESES™). SESES™ is a suite of programs permitting to simulate sensor and actuator devices by means of a 2D and 3D finite element method.

Compared to silicon membrane sensors, the thermal losses by conduction through the oxynitride membrane are significantly reduced allowing to shrink the die size area taking account of the essential following requirements:

- The temperature homogeneity over the SnO_2 layer has a direct impact on the sensitivity and selectivity of the sensor. So, the temperature gradient over the sensitive area should not exceed 50°C to keep sensitivity performances.
- The SnO_2 area must be kept in the same dimension (1 mm^2)
- Ohmic contact temperature must be less than 300°C to avoid electro-migration and interdiffusion of metal in silicon
- Power consumption must be as low as possible

Simulations have been performed assuming the following boundary conditions:

- according to experimental observations, the temperature at the periphery of the die is constant and equal to 30°C
- on the upper and lower surfaces of the membrane, heat is dissipated through convective exchange with the gaseous phase. The exchange coefficient is taken respectively as 250 and 125 $W/m^2.K$.
- radiation losses have been considered as negligible.

According to the criteria listed above, the effect of the length of the polysilicon heater (L), the size of the hole in the polysilicon heater (l) and the membrane area (A), on the temperature distribution and power consumption have been evaluated. All the simulations have been performed at Tmax. = 450°C and for a 1.5 µm membrane thickness.

From this results, it turns out that the temperature homogeneity over the sensitive layer depends on the membrane area.

The reduction of the heater length and hole area induces an increase of the heater contact temperature, on the contrary to the membrane area reduction.

The power consumption decreases with the reduction of the heater length while it increases with a decreasing of the membrane area.

Moreover, it has been shown by simulation that convection and conduction losses account respectively for 75% and 15 % of total losses.

As a result, a new structure has been proposed offering the best trade off between performances and the size reduction required by cost considerations.
It consists in a rectangular die (2300 x 2100 μm^2) with L = 600 µm, l = 100 µm, A = 1000 x 800 μm^2 and E =1.5 µm (Figure 2.).

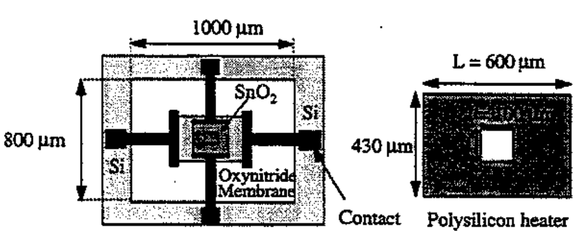


Figure 2. Schematic view of the new sensor structure obtained by simulations (Top view)

EXPERIMENTAL VALIDATION OF SIMULATED STRUCTURE FOR THE OPTIMIZED SENSOR

Thermal performances have been characterized using an Infra Red camera AVIO 2100. Experimental thermal IR measurements have confirmed the validity of the predictions obtained with SESES simulations. Table 2 shows the main thermal characteristics of the sensors as predicted in the simulation and then verified experimentally.

As a result, the power consumption at the operating temperature of 450 °C has been divided by three using a silicon oxynitride membrane instead of a silicon membrane (Figure 3.) Moreover, accelerated tests have shown a life time up to eight years (Figure 4) confirming the good mechanical strength of the oxynitride membrane.

Table 2. Comparison of the experimental measurements with the simulations of the thermal performance of the oxynitride membrane (5 W/m.K.) for Tmax = 450C°.

Power Consumption (mW)		Average Temp. over sensitive layer (°C)		Heater Contact Temp. (°C)	
Exp.	*Simu.*	**Exp.**	*Simu.*	**Exp.**	*Simu.*
60	*59*	**420**	*420*	**247**	*240*

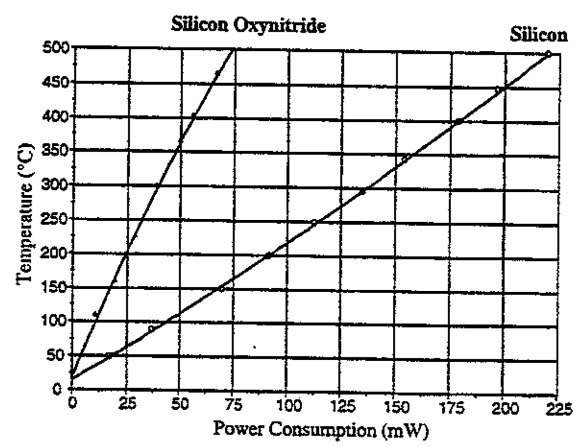


Figure 3. Comparison of the power consumption as a function of temperature between silicon oxynitride and silicon membranes

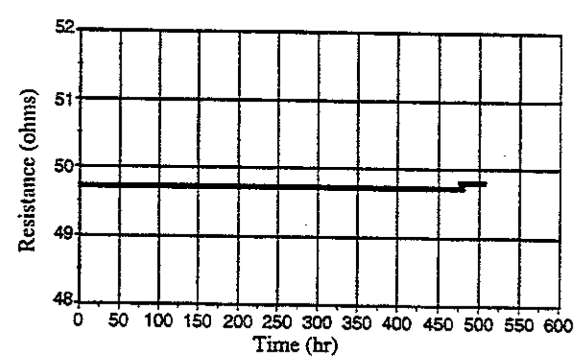


Figure 4. Resistance of the polysilicon heater during power cycles (12 000 cycles per hour)

CONCLUSION

To reduce the power consumption of an integrated tin oxide gas sensor, we propose a new solution using a silicon oxynitride membrane SiO_xN_y. This membrane obtained with a single process step, exhibits a low thermal conductivity and a high mechanical strength giving above 95% fabrication yield.

Based on simulation, we have put forward a new geometry for the whole sensor associated with the presence of an oxynitride membrane. Thermal losses due to conduction being limited, we were able to reduce by half the overall surface of the sensor without altering its performance.

A micro gas sensor integrated on silicon including an oxynitride membrane has been developed.

This sensor fully meets the set of specifications we had laid down with respect to:

. mechanical strength .

. temperature homogeneity over the sensitive layer

. decrease in electric consumption (divided by 2,5)

decrease the die size (800 Die Per Wafer with a silicon membrane 1600 Die Per Wafer with a silicon oxynitride membrane)

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