Antifuse nano-hot-spot device on a suspended membrane for gas sensing applications

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Abstract— **We have designed and realized a new antifuse hot-spot device to be used in gas sensing applications. The antifuse structure was realized on a suspended membrane to minimize the heat losses. For the sensing of alkanes a procedure for making a porous alumina layer doped with Platinum was developed. The device was electrically characterized and gas sensing experiments were conducted.**

Keywords—**antifuse, hot-spot, suspended membrane, sacrificial layer, silicon, MEMS, gas sensing**

I. INTRODUCTION

Sensing of combustible and potentially explosive gases is of a great importance for many fields of activity ranging from household appliances to industrial applications. The challenge is to realize a sensing device which has a fast response but on the other hand should be efficient, that means it requires the lowest possible electrical power. This is very important when using in portable detectors or in remote locations. This was the main task in the frame of the SAFEGAS, a European project meant to design and realize a fast, low power gas sensor for explosive gases as Methane, Butane, Propane, etc.

This paper summarizes some of the results of our studies, using CMOS-compatible processing techniques, to realize a pellistor-type gas sensor, highly efficient as required.

Previously a pillar-shaped silicon structure was realized and characterized [1].

II. MAKING OF THE SUSPENDED MEMBRANE ANTIFUSE NANO-HOT-SPOT DEVICE

A. The antifuse

An antifuse is formed by forcing a current through a very thin layer (10 nm) of silicon oxide in between two highly doped 2 um wide poly-silicon electrodes, until the breakdown of the oxide is achieved and some of the material melts locally so that a link is formed in between the two electrodes. This process is called programming of the antifuse.

If a voltage is applied afterwards and a current is forced through the structure, lower than the one corresponding to the initial programming then the formed antifuse has a resistor-like behavior, so that it could generate heat.

The size of the active hot-spot is in the sub-micron range, 50 to 100 nm depending of the programming current.

B. The suspended membrane

To minimize heat losses, the antifuse device was fabricated on a 100 nm thick stress free silicon nitride suspended membrane. This was realized after completion of the device, by combining techniques of surface and bulk micro machining of underlying layers. Windows were etched in the membrane layer and a anisotropic wet etch was performed in a solution based on tetra methyl ammonium hydroxide (TMAH) [2] to remove the underlying poly-silicon sacrificial layer and moreover, get an inverted pyramid cavity in to the silicon substrate. Figure 1 shows a schematic of the device. One can see the two electrodes and the link formed in between, everything on top of the suspended membrane. The thin nitride layer for the membrane was deposited on to a oxide layer for extra thermal insulation. For gas sensing applications the temperature and the size of contact area with the gas are of a great importance for a good sensing efficiency. As a consequence, to get a more uniform temperature distribution over a larger area, a 10 µm diameter disk of poly silicon was realized on top of the hot-spot. This disk acts as a micro hot-plate. Then the structure was covered by a porous alumina layer which contains a Pt-based catalyst.

A SEM picture of the device realized as above is presented in figure 2 where one can see the cavity etched underneath the membrane. A cross-like geometry of the contacts was chosen in order to have a certain area where the breakdown occurs and to allow for measuring the voltage drop across the antifuse.

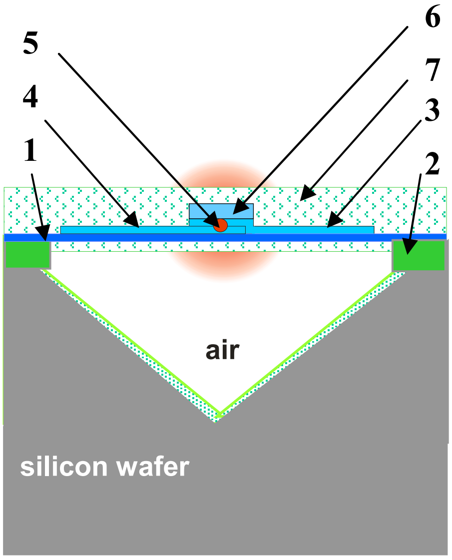

Figure 1: Schematic of the suspended membrane nano-hot-spot device. One can see the cavity etched in to the silicon substrate underneath the suspended membrane 1 which was grown on a 500nm oxide layer 2. The device consists of the link 5 formed in between two poly-Silicon electrodes 3 and 4 and the thicker disk of poly-Silicon 6 on top of them. Everything, including the inner walls of the cavity and backside of the membrane, is covered by a porous Alumina layer 7 containing a Pt catalyst.

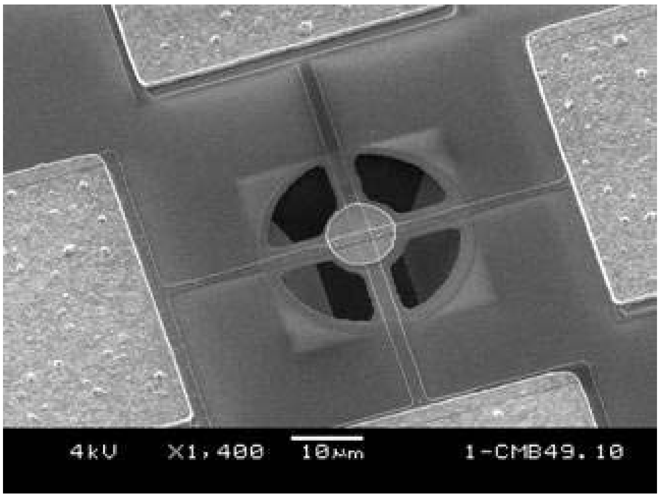

Figure 2: A SEM picture of the device shows the cavity and the electrodes running across the suspended membrane in between the Al bonding pads. The link is formed in the square region where the electrodes overlap and it is too small in size to be noticed underneath the top electrode and the 300 nm thick "hot-plate".

III. ELECTRICAL CHARACTERISATION

A. Method and setup

The devices have been electrically characterized on a CASCADE multiprobe station coupled to a precision semiconductor parameter analyzer Agilent 4156C. As shown in figure 3 a current was forced between the electrodes 1 and 3 and the voltage across 1 and 3 and across 2 and 4 as well were recorded. This allows to measuring the total electrical resistance of the structure (Rtot), i.e. the resistance of the antifuse link in series with the resistance of the poly-silicon electrodes and at the same time the resistance of the link only (RS) when a current IF is applied in between two adjacent contacts (poly-Silicon electrodes) and voltage is measured at the other contacts. The method offers the advantage that driving and measuring of the device are decoupled.

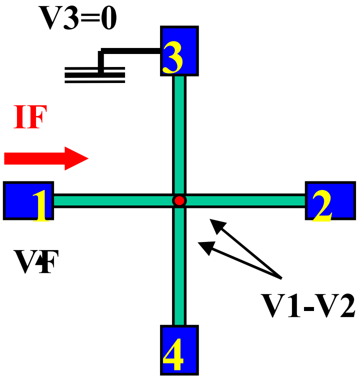

Figure 3: Schematic of the measurement design. Current is forced through the structure (1 and 4) and voltage is measured in between 1 and 3 (total voltage) and in between 2 and 4 (voltage across the link).

B. Re-programming of the antifuse

When applying a high current to the antifuse, we notice an increase of the resistance of the link and then a change in slope. If the driving current of the antifuse is higher than the current corresponding to the original programming as explained above, we can conclude that the temperature rises up to the intrinsic point of silicon at about 1000 ^{0}C corresponding to the maximum of the curves in figure 4 when the carrier concentration reaches the doping concentration and further on it reaches the melting point at 1417 ^{0}C (the descendent curve) when the antifuse is reprogrammed getting larger in size. As a consequence, the corresponding electrical resistance of the link shifts to a lower value as shown in figure 4.

In general, the link can be re-programmed as above to meet the current and power requirements for a specific application. Re-programming of the device is not a reversible phenomenon but operating the device below the intrinsic point is always safe and reproducible.

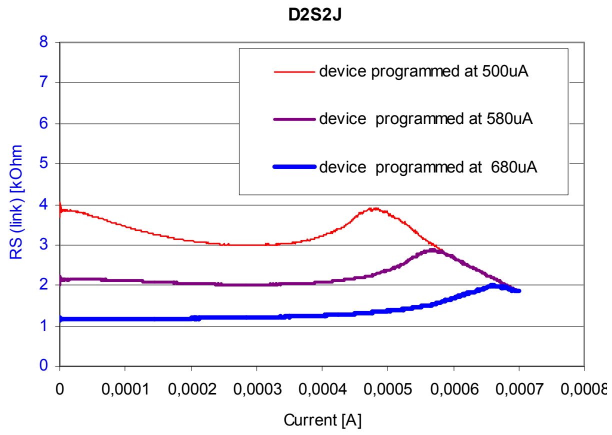

Figure 4: Re-programming of the antifuse. Electrical resistance of the link as a function of current gives an indication of the temperature of the link at high currents. The maximum of the curve corresponds to the intrinsic point of Silicon at about 1000 ^{0}C and further on the device reaches the melting point of 1417 ^{0}C on the descending curve when the antifuse is reprogrammed and the next curve will start from the new lower value of RS.

C. Resistance of the link as a function of current

From the typical plot of the resistance of the link vs. current in figure 5, one can observe that at low currents the resistance of link is almost constant. At high currents both curves have a steep increase. We can conclude that in this region both the link and the highly doped poly-Silicon electrodes show a metal-like behavior. If we plot the differential variation ΔRS/RS and ΔRtot/Rtot as in figure 6 we can observe that at high currents the link plays a major contribution as the increase of RS is more than 80% compared to only 40% increase for the total resistance.

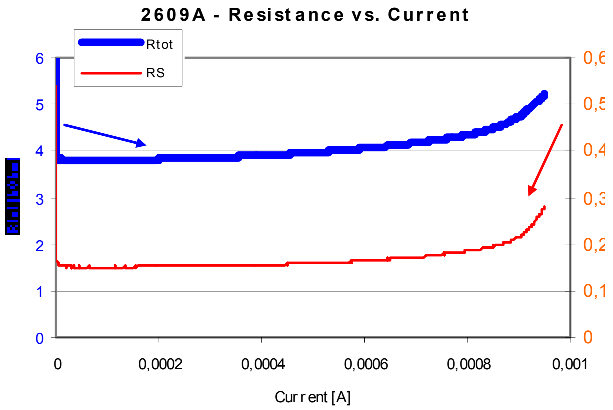

Figure 5: Electrical resistance of the link RS and total resistance as a function of current. The increase of resistance at high currents is due to an increase of the temperature of both the link and the electrodes

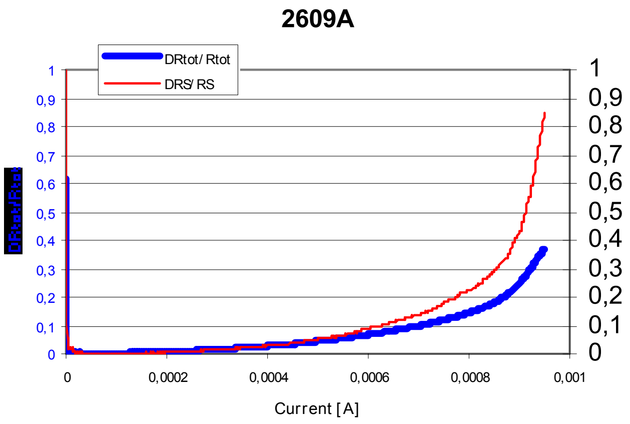

Figure 6: Resistance of the link RS increases faster than the total resistance, hence resistance of the poly-Silicon electrodes

IV. GAS SENSING EXPERIMENTS

A. Principle of operation for sensing of combustible gases

As the device is too small to allow for a direct measurement of the nano-hot-spot and hot-plate temperature by techniques available to date, we can only estimate this temperature from the electrical characteristics as shown in the figures 4 to 6 as explained above.

The temperature necessary for sensing combustible gases when using a catalyst is much lower so that we can operate the device safely at a lower power and subsequently we avoid reprogramming of the device. For gas sensing we can use the same setup as above, the same geometry of the contacts and apply a constant current monitoring the resistance vs. time. In normal conditions in air, the total resistance Rtot and

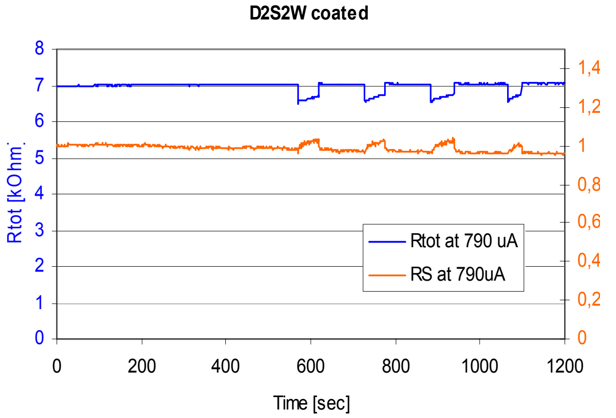

Figure 7: Sensing of Butane. In the presence of gas the electrical resistance of the link RS (lower plot, right y axis) increases due to an increase of temperature caused by catalytic burning of gas in to the pores, whereas the total resistance Rtot (upper plot, left y axis) decreases due to a thermal conductivity effect caused by Butane.

the link resistance RS should be both constant at values corresponding to the current applied. The temperature of the link and the hot-plate covered by the porous layer again is a function of power, hence constant. When a combustible gas, Butane in our experiments, gets in to the pores reacting with the catalyst, it is burnt locally and gives an extra amount of heat that means a higher local temperature that is reflected in an increase of the resistance of the link we measure as in figure 7.

The decrease in total resistance Rtot (upper plot) may be related to a thermal conductivity effect of the gas that takes place between the membrane and its poly-Silicon patterns and the cavity walls. Since the poly electrodes are on average closer to these walls than the hot plate they are more sensitive to conductivity changes. This may counteract the increase of the resistance of the link RS (lower plot) in the presence of Butane, which is definitely a result of the catalytic activity as explained above. By using a device with catalyst and one without catalyst in a Wheatstone bridge design the changes caused by the thermal conductivity effect can be ruled out.

V. ACKNOWLEDGMENTS

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VI. CONCLUSIONS

We have designed and realized an antifuse nano-hot-spot device on a suspended membrane to be used in combustible gas sensing applications.

We developed the technology operations for etching the sacrificial layers underneath membrane, to cover the structure with an alumina porous layer and adding and activation of catalyst which will be described in some more detail somewhere else.

We demonstrate the ability of the device to sensing of Butane.

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