Nanosecond Range Heating and Temperature Measurement on Thin Layers

Experiment and Simulation

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ABSTRACT

A chemical semiconductor sensor for oxygen gas was activated by thermal treatment. The thin Pt layer of the n-$Si/SiO_2/Si_3N_4/LaF_3/Pt$ field effect structure was used as the gate electrode for sensitivity measurements, heating resistance and temperature sensor. Taking advantage of using the gate electrode for heating only the sensitive two layer system LaF_3/Pt (thickness only 300 nm) has to be at high temperature. The reactivation was shown to be a very fast process. Within a period of 10µs the structure was heated and the activation process was completed. The temperature measurement was done using the voltage drop at the gate and the current of the heating impulse. For the temperature measurement a resolution on the time scale of nanoseconds was achieved. The time dependent temperature distribution in the sensor multi layer structure was simulated using the CFD-ACE+ software of CFDRC. For the µs-impulses the temperature increase of only the thin layers and not the silicon bulk was shown.

Keywords: sensor, heating, thin layer, temperatur measurment

INTRODUCTION

Recently, we developed an all-solid-state oxygen sensor based on semiconductor technology [1]. In contrast to other sensors this device combines the advantages of measuring at room temperature and an all solid-state principle.

The field effect semiconductor structure used in our experiments was an n-$Si/SiO_2/Si_3N_4/LaF_3/Pt$ layer system (Fig. 1). The freshly prepared sensors showed a fast response. The t_{90}-time of this sensor was typically around 90s. A disadvantage of this sensor system was that the sensor response was getting dramatically slow after several days. This behavior was found to be reversible. A simple thermal treatment (300 to 350°C) reactivated the sensor. However, since the whole sensor was heated, a long thermal drift of the sensor signal was observed while the structure was cooling down. To avoid this problem, the Pt-layer was modified to use it as a heating resistor. Only two of the layers, LaF_3 and Pt, interact with the analyte. Hence, only these two layers had to be heated. To get a minimum increase in temperature of the whole sensor structure, only very short electrical pulses (<100µs) had to be applied. The thermal drift problem was minimized this way. Applying

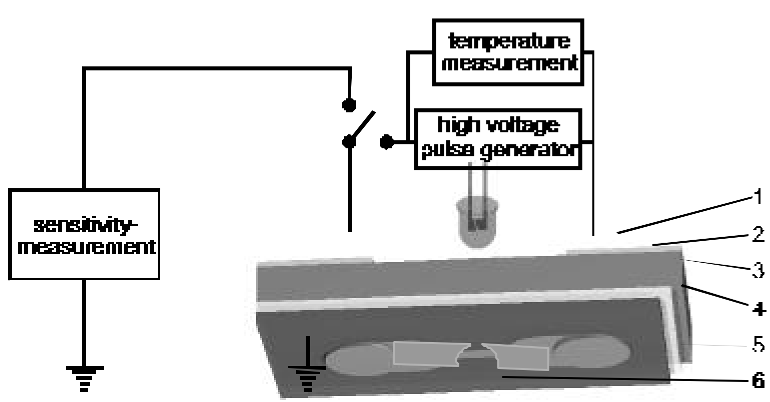

Fig. 1 Sensor structure: 1 - Pt layer; 2 - LaF_3 layer; 3 - SiO_2/Si_3N_4 layer; 4 - n-Si; 5 - ohmic contact (Al); 6 – photo diode and blind frame. Three different techniques use the Pt layer for measurement and thermal treatment.

this modified activation procedure, it was possible to activate the sensor within 10µs at a power of about 800W during this short heating period, i.e. the electrical current flowing through the platinum film was about 10^7 A/cm^2[2,3]. For the investigation of the kinetics of the reactivation process the temperature during the electrical µs and ns pulses had to be measured. It was the aim of this paper to demonstrate our developments on a very fast method of surface temperature measurements. The temperature distribution in the nanometer scale multi layer structure was simulated using the CFD-ACE+ software of CFDRC.

EXPERIMENTAL

The sensor structures were produced using n-type Si(111) with ρ = 10 Ohm*cm. Thin films of LaF_3 were prepared by thermal evaporation in a vacuum from LaF_3 pellets. The vacuum during evaporation was better than $5*10^{-6}$mbar, the substrate temperature was 823 K, the rate of evaporation 0.3 - 0.6 nm / s and the film thickness 240 nm. The DC cathode - sputtering method was used to fabricate Pt thin films (60 nm) in the geometry shown in Fig.1. The ohmic contacts to Si were made with thin films of Al.

For the characterization of the sensor structures, photocurrent measurements were used allowing the sensitivity determination to be concentrated on the small impulse heated Pt-band between the contacts. The oxygen sensitivity was determined at room temperature. Temperature measurements based on a 4-point probe allowing voltage drop and current measurements directly while applying the heating impulse. A laboratory made device was used to create ns- and µs high voltage – high current electrical heating impulses. Current and voltage were recorded using the digital oscilloscope Le Croy 9450A.

RESULTS AND DISCUSSION

To investigate the kinetics of the reactivation process the temperature during the electrical µs and ns pulses had to be measured. We used the change of the resistance of the heater itself to establish a new method for measuring surface temperatures in this very short time scale.

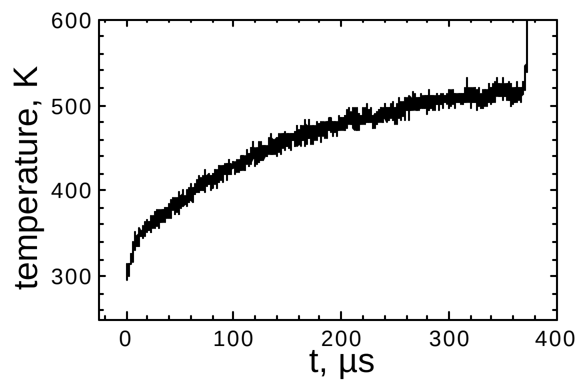

Fig. 2 In-situ surface temperature measurement during an electrical heating pulse P=100,9 W; the increasing resistance at the end of the curve has its reason in the destruction of the film.

The representation of temperature/time curves was achieved with a resolution in the ns range. The resistance of the Pt-layer (small region between the contacts; see Fig.1) was calculated from the current and the voltage drop. A calibration

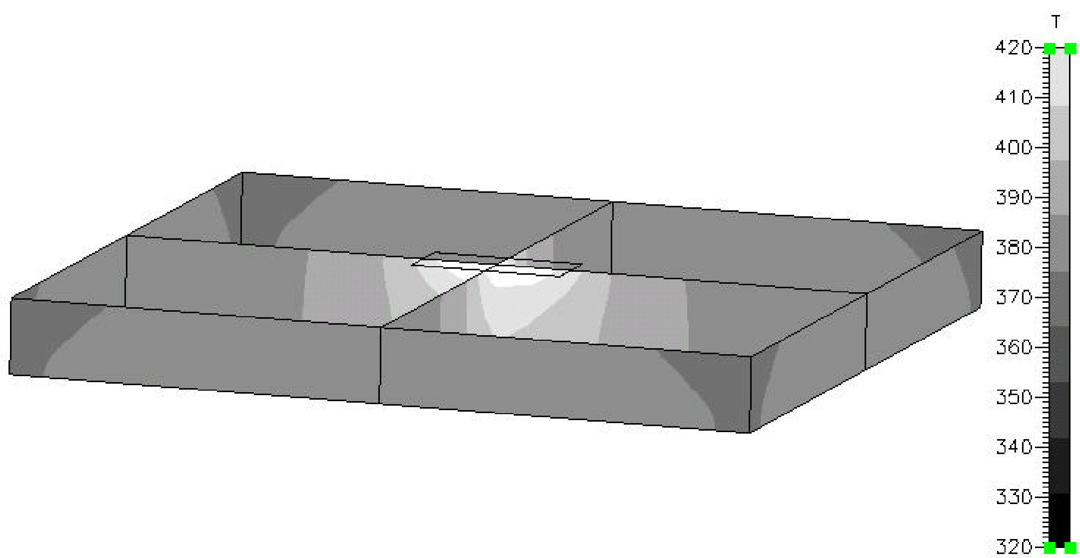

Fig. 3 Calculation of temperature distribution in the Si-chip, the small rectangle on the top represents the heated Pt-layer; heating power 10W; heating time 1 s

was achieved by external heating of the sensor and a measurement of the resistance at energies small enough to neglect additional electrical heating. An example for temperature rise measurements is shown in Fig. 2. For this experiment a power of 100 W was applied to a 60 nm thick Pt-layer.

Comparing different heating conditions we found changes in the temperature/time curve form for different heating impulse length.

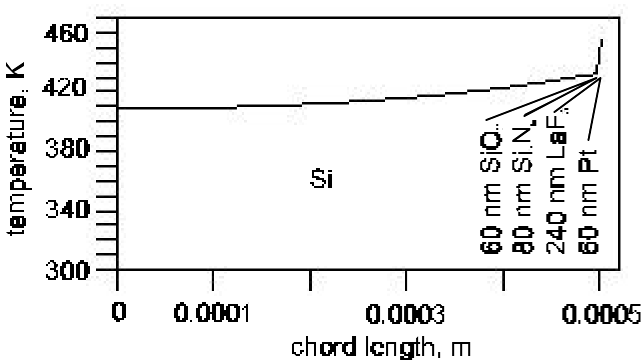

Fig. 4 Temperature profile for long time electrical heating impulses; heating power 10 W; heating time 1 s

The time dependent temperature distribution in the sensor multi layer structure was simulated using the CFD-ACE+ software of CFDRC. A special problem of our structure was the combination of very thin layers (SiO_2 (60 nm); Si_3N_4(80 nm); LaF_3(240 nm) and Pt(60 nm)) and a relatively thick substrate of 500 µm. According to the experimental conditions only the central part of the thin Pt-layer (0.5*1.5 mm^2) was used as a heat source for the calculations. The applied power and the time was varied. The initial temperature for all components was 300 K.

It was shown that for long electrical heating impulses (100ms-1s) the whole structure becomes hot. This is illustrated in Fig. 3 and 4. The very thin layers (nm range) and the size of the chip 5*5*0.5 mm^3 results in the problem of graphic representation of temperature distribution in Fig.3. Therefore a temperature profile from top to bottom of the chip is given in Fig.4. There is a strong gradient in temperature in the thin layer system due to the bad thermal conductivity of the insulators but the Si-bulk is heated to a temperature more near to the temperature of the Pt than to the initial value (300 K).

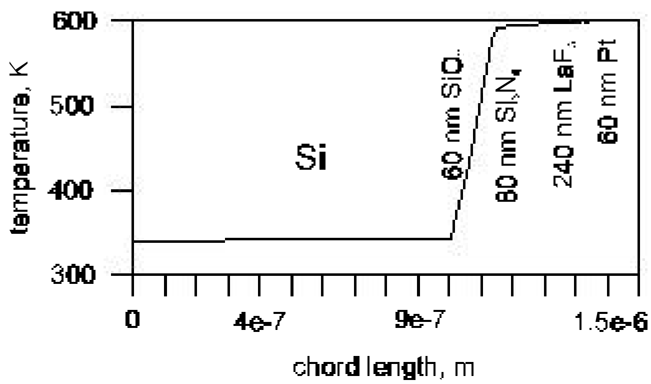

Fig. 6 Temperature profile for short electrical heating impulses; heating power 100 W; heating time 10 µs

In contrast to this (see Fig. 5 and 6), for short impulses (<100µs) only the very thin Pt- and the LaF_3-layers are heated to a high temperature, while the semiconductor

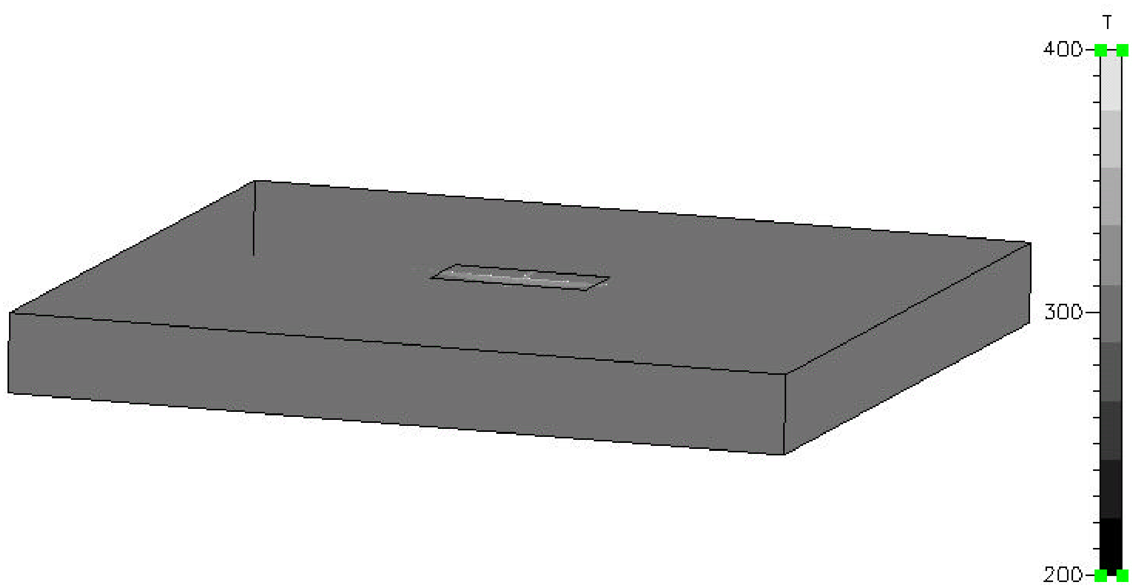

Fig. 5 Calculation of temperature distribution in the Si-chip, the small rectangle on the top represents the heated Pt-layer; heating power 100 W; heating time 10 µs

remains practically at room temperature. The nearly constant temperature of the Pt- and the LaF_3-layers is due to the high thermal conductivity of these materials. In Fig. 6 the scale is different to Fig. 4 showing only 1 µm of the Si-bulk (total 500µm). Even that near to the heater the temperature is still near to the initial value.

CONCLUSIONS

The result of this calculations is in accordance with the demands of reactivation of these two chemically active layers. It was surprising that even the first µm of silicon near to the insulator is fairly cold for such short time heating. Therefore, no thinning of the Si-wafer is necessary as usual for other heaters. Furthermore, we found from the simulation that the whole sensor structure is at low temperature within ms after switching off the heating. The relation between experimental surface temperature measurements and the time dependent simulation proved to be of good quality. Both did show a change in temperature/time curves using very short heating times. Experiments and simulations using more complex electrical impulses leading to constant surface temperatures in the sub µs range are in progress.

Additional characterization of the Pt-layer after the high power heating will be given using thermal microscopy and AFM.

References

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