A Micro-Scale Hot-Surface Device Based on Non-Radiative Carrier Recombination

A. Y. Kovalgin, J. Holleman, G. Iordache

MESA⁺ Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

E-mail: a.y.kovalgin@utwente.nl

Abstract

This work employs the idea of making micro-scale hot-surface devices (e.g. sensors, flow meters, micro reactors, etc) based on generation of heat due to non-radiative recombination of carriers in a thin (13 nm) poly silicon surface layer. An important part of the device is a nano-scale (10-100 nm) conductive link created between two polysilicon electrodes separated by a dielectric (a capacitor-like structure). Using this approach, we designed and realized a new silicon device with the hot surface reduced to a sub- μm -size area, operating at very low power down to sub- μW . From the experiments, such a device can be used as a heat source as well as a sensitive detector of heat. In this paper, we describe thermo-electrical properties of fabricated devices and demonstrate their feasibility to perform as gas- adsorption- desorption sensors operating at extremely low power consumption.

1. Introduction

For characterization and manipulation of nanoscopic quantities of matter, scientists presently rely on highly specialized and expensive equipment. In this paper we present a new, simple and cheap device (the so-called pillar-shaped antifuse), which when integrated on a chip, can allow *in situ* characterization of physical and chemical processes on micro/nano scale (e.g. adsorption and desorption) including thermo activated reactions. As such it can contribute to some of the present-day scientific challenges (e.g. molecular electronics).

As a particular example, hot-surface devices have received much attention because of its utilization for Pellistor-type gas sensors [1] and micro reactors. One significant drawback of a conventional Pellistor is its relatively high power consumption (tens of mW). Our approach employs the idea of maintaining a micro-scale hot surface by means of generation of heat due to a non-radiative carrier recombination in a thin electrode made of poly silicon. The structure has two electrodes separated by a nano-scale conductive link created in a thin silicon dioxide layer by means of a dielectric breakdown. It appears from the modelling and measurements that, whilst the entire surface electrode behaves as a heat generator, the device itself can perform as a sensitive heat detector [2]: its electrical resistance is a sensitive measure of temperature. These properties

combined with extremely low operating power in a (sub)- μW range give rise to a number of practical applications, for example, in the field of low-power gas- and flow sensors, temperature detectors (a. o. for scanning probing techniques), sensing/actuating units for a lab-on-a-chip, etc.

Apart from the low power consumption, an advantage of the device is decoupling of the electrical resistance and thermal resistance. In a conventional hot-plate device, the heat is generated either by a filament heater or suspended meander. In such a design, an increase of thermal resistance of the electrical leads is an important issue due to the necessity to minimize the power loss through the leads. Indeed, an increase of the thermal resistance can only be achieved by shrinking the cross-sections, which leads to the increase of electrical resistance resulting in undesired extra power dissipation in the leads. Our devices allow an independent control of both the resistances. This becomes possible because the electrical resistance is now mostly determined by the link resistance and has very limited influence on the thermal resistance due to the nano-scale link dimensions.

2. Experimental

For our pillar-shaped devices, the hot surface is thermally isolated from the bottom silicon electrode by means of a 500-nm LOCOS oxide (Fig 1). The technology also ensures pre-determination of the link location on the surface. The structure consists of two electrodes: rather thick mono-Si pillar-type bottom electrode and very thin poly-Si top electrode passivated with silicon nitride. The surrounding oxide plays an important role for thermo-electrical isolation and confines the area of antifuse formation.

Fig 1. Schematic of a pillar-shaped device.

The process flow employs standard LOCOS oxidation and CVD technology. As the first step, an LPCVD silicon nitride film was deposited on a phosphorus-doped (100)-oriented silicon wafer with a resistivity of 2-5 $\Omega\cdot\text{cm}$. After patterning the nitride ($2\times 2\ \mu\text{m}$ squares), approximately 1- μm high silicon pillars, covered with the nitride caps, were formed on the wafer surface using isotropic $\text{CF}_4\text{-O}_2$ plasma etching. The following LOCOS oxidation at 1050 $^\circ\text{C}$ provided sharpening the pillars and formation of a 400-nm silicon oxide for thermo-electrical isolation of the pillars. Further, the silicon nitride was etched away, and a thin gate oxide (10 nm) was grown on the silicon tip surface. Then, a 13-nm thick in-situ phosphorus-doped a-Si layer ($\sim 10^{20}\ \text{at}/\text{cm}^3$) was deposited on the wafer surface, followed by LPCVD of a 9-nm thick silicon nitride layer for passivation of the device surface. The SEM image of a realized device is presented in Fig 2.

Fig 2. SEM top-view image of a fabricated device.

The conductive link between the two electrodes (i.e. an *antifuse*) was initially caused by electrical breakdown due to tunnelling a constant current stress through the 10-nm thick gate oxide. Finally, we applied a well-defined programming current, which is higher than the initial stressing current, to enlarge the link [3]. It appears from our research that as the link is once created at certain value of the programming current, the size and electrical properties of the link cannot be changed under a current stress below the programming value. Both the programming and electrical characterisation have been carried out using a parameter analyser Agilent 4156C.

3. Experimental Results and Discussions

We have investigated the electrical properties of the realized devices and their feasibility to perform as gas-adsorption-desorption sensors.

The I-V characteristics reflect a non-trivial behavior of the devices (Fig 3). At near-zero bias, the device resistance is very high. A gradual increase of the bias (positive sign, applied to the poly-Si electrode) leads to rather sharp increase of current. Applying a negative bias causes much higher device resistance compared to

positive biasing. In this light, the thin-film antifuse with the same type of electrode doping behaves similar to a diode. This rather interesting result can be attributed to depletion-related effects in the mono-silicon electrodes at a negative bias.

Fig 3. Diode-like I-V characteristics of pillar-shaped antifuses with the same type of electrode doping.

The concept based on depletion is confirmed by the following results. First, the measurements were carried out for a number of the pillar-shaped devices with a different degree of sharpness of the pillar. It appears that only rather sharp pillars are able to maintain low currents under high negative biases up to -100V . If radius of the tip increases (i. e. less sharp pillar), the diode-like behaviour becomes less distinguishable. At certain tip radius the diode-like behaviour disappears. Second, the ability of the devices to maintain low currents at high negative biases is also affected by the conductive link diameter. A low current at a high negative bias can only be established for low programming currents meaning that the conductive link is relatively small and not able to provide enough carriers (electrons) to suppress the depletion in the pillar. Third, the numerical simulations confirm the above-mentioned conclusions (Fig 3).

Fig 4. I-V characteristics of a pillar-shaped antifuse at different substrate temperatures; bias is applied to poly-Si electrode.

The depletion effects in the pillar cause the sensitivity of the device resistance to substrate temperature only when a *negative bias* is applied (Fig 4). Namely, due to a low concentration of free carriers in the close-to-link area of the sharp silicon pillar, the pillar resistance becomes a sensitive measure of temperature. The extra heat supplies new carriers, which leads to the resistance drop. The sensitivity of such a heat sensor is very high – about 0.7 Volts per degree.

A number of stability tests have been carried out. The devices were kept at 30% of the programming power for 24 hours. It means that the core of these devices was significantly lower than the melting point of Si (1415 °C). We noticed rather good stability in time and expect only minor instabilities due to thermal degradation under normal operating conditions.

To clarify, whether the devices are able to generate enough heat for the successful actuation of physical and chemical processes on the surface, we have carried out the following experiments. It has to be emphasized that the devices are not only intended to maintain certain temperature on the surface but also to monitor the temperature change, which is a measure of the surface process. Therefore, only experiments at a *negative bias* have been carried out. Interesting results have been obtained with respect to vapour sensing. In Fig 5, one can observe a significant response after introducing a mixture of ethanol vapour with air into the measuring chamber. Similar response to acetone and isopropanol was also obtained but no response to water vapour.

Fig 5. Device response after introducing 6.6% ethanol vapour into the chamber; a low power of 0.9 μ W is applied.

It was noticed that thermal conductivity did not play a role (i.e. no response after the substitution of synthetic air with CO₂ was observed). From the fact that the response peaks are directed downwards, we can further conclude that the resistance of the device decreases after the vapours are introduced into the measuring chamber. This change of the resistance can be attributed to a temperature increase caused, for example, an exothermic process (combustion, decomposition) near the device surface. If such a process takes place, the produced extra heat will increase the device temperature and cause the resistance drop according to Fig 5. The autoignition temperature is 538 °C for acetone and 363 °C for ethanol

[4]. This can give a rough indication of the surface temperature. It is important to bear in mind that no catalytic layer aiming at decreasing the operating temperature was deposited on the device surface.

As the next step, the pillar-shape devices were coated with a porous 350 nm thick Spin-On-Glass layer. First experiments on measuring gas-sensing effects for the coated devices have been carried out in a thermal conductivity mode (Fig 6). This means that the surface temperature was not high enough to initiate exothermic reactions. In this mode, the devices were able to sense the adsorption/desorption processes occurring in the porous material and influenced by the surface temperature. A cycle depicted in Fig 6 can be explained as follows. After the vapour is introduced into the chamber, the adsorption occurs in the porous SOG layer. This cools down the surface and causes an increase of the resistance. As a consequence, an extra bias (i.e. extra power) is applied to maintain the same constant current. In the beginning, this extra power enhances the desorption rate and causes further cooling the surface, which again requires applying an extra bias to maintain the same current. Such a self-amplification mechanics results in a very sharp increase of the bias after the mixture is introduced into the chamber (Fig 6). A very high response of about 40 Volts combined with a high sensitivity and lower power consumption make such a device rather interesting for measuring adsorption and desorption processes.

Fig 6. Device response after introducing 1.3% ethanol vapour into the chamber. The device surface is additionally covered with a 350-nm thick porous SOG layer. Maximum power of 4 μ W is applied, standby power is 0.5 μ W.

Similar effects were observed for acetone and water vapours. A high response to water vapour confirms the conclusion that exothermic mechanisms are not activated and either cooling or heating the surface due to the adsorption/desorption cycles takes place. With increasing the standby power up to 10 μ W, we have noticed a suppression of the adsorption of water, indicating a higher surface temperature. The experiments on further increase of power up to hundreds of microwatts are ongoing. We expect to achieve higher surface temperatures able to initiate thermal decomposition of organic compounds.

We have also observed response delays depending on vapour concentrations. As expected, the delay is more pronounced for lower concentrations. This is due to the fact that, for low concentrations, the adsorption is limited by the supply. The response delay effect can be utilized e.g. for a chromatographical analysis.

4. Numerical Simulations

To verify the ability of the pillar-shaped antifuses to maintain a surface temperature of about 400 °C (approximately corresponding to the response shown in Fig 5) at power consumption in the μW range, we have carried out numerical simulations using SILVACO code [5]. Based on the diode-like behaviour (Fig 3), one can consider two mechanisms of heat generation. The first mechanism corresponds to a *positive bias* applied to the poly-Si electrode. In this regime the heat is dissipated in the link, which acts as a resistor. The heat is further distributed in lateral and vertical directions. The lateral heat transport is limited due to the thickness of the poly layer. The vertical heat transport downwards enhances the heat losses because of the massive silicon pillar. In this regime, the efficiency of the heat generation is low due to the vertical losses.

To activate the second heat generation mechanism based on a non-radiative carrier recombination, a *negative bias* is applied to the poly-Si electrode. From the simulations, the carrier recombination occurs in this regime along a significant area ($\sim 2 \mu\text{m}$ in diameter) of the poly electrode. This area is much larger with respect to the nano-scale link area. The result is that the entire area instantly becomes hot and the lateral heat transport processes can be neglected. Consequently, the vertical heat losses through the pillar play a less important role with respect to the first regime. Finally, this leads to a higher surface temperature.

Fig 7. Simulated surface temperature profiles.

The considerations made are confirmed by the numerical simulations. As one can see in Fig 7, the difference in temperature between the two regimes is more than two orders of magnitude. Also the surface temperature distribution for the second regime exhibits a more flat profile. Furthermore, a temperature drop in the centre (link) clearly indicates a heat sink because of the pillar. With increasing the applied power beyond 0.1 μW some

problems related to the convergence of the solutions have occurred in the simulator. However, from Fig 8 it can clearly be seen that, in case of a negative bias, the power required for increasing the surface temperature within one degree decreases with increasing total applied power. Extrapolating, one can expect a value of a few nW per Kelvin for a power of 0.2 μW . On the other hand, for a positive bias the power per Kelvin gradually increases with applied power. The difference between the two curves is more than three orders of magnitude.

Fig 8. Power per one degree of surface temperature versus total applied power.

5. Conclusions

Both the experiments and simulations indicate that the pillar-shaped devices are able to maintain a surface temperature as high as a few hundred degrees centigrade at a power consumption in the (sub)- μW range. The size of the hot area and its temperature can be manipulated by the sign of the applied bias. Two different heat generation mechanisms (dissipation at a resistor and a non-radiative recombination of carriers) play a role. In addition, the devices exhibit a high sensitivity to external heat and can be employed as gas- adsorption- desorption sensors. These properties together may allow the devices to be used e.g. in a versatile miniature lab-on-a-chip for sensing and actuating nanoscopic quantities of matter.

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