Research Article

Characteristics and Breakdown Behaviors of Polysilicon Resistors for High Voltage Applications

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With the rapid development of the power integrated circuit technology, polysilicon resistors have been widely used not only in traditional CMOS circuits, but also in the high voltage applications. However, there have been few detailed reports about the polysilicon resistors' characteristics, like voltage and temperature coefficients and breakdown behaviors which are critical parameters of high voltage applications. In this study, we experimentally find that the resistance of the polysilicon resistor with a relatively low doping concentration shows negative voltage and temperature coefficients, while that of the polysilicon resistor with a high doping concentration has positive voltage and temperature coefficients. Moreover, from the experimental results of breakdown voltages of the polysilicon resistors, it could be deduced that the breakdown of polysilicon resistors is thermally rather than electrically induced. We also proposed to add an N-type well underneath the oxide to increase the breakdown voltage in the vertical direction when the substrate is P-type doped.

1. Introduction

With the booming market of power integrated circuits for the smart power management [1–4] and automotive and green energy, BCD [5, 6] (Bipolar-CMOS-DMOS) technology has been proved to be the best solution for these applications. People tend to integrate as much active and passive devices, including resistors, for different voltages' applications as possible on single chip. As a resistor, polysilicon [7] is supposed to be the best choice for integrated circuits technology due to its good and stable voltage and temperature coefficients. However, in the high voltage application, although the polysilicon resistor is still acting as an important device, there are few detailed reports about its properties, especially the voltage and temperature coefficients, under high voltages. It has been experimentally observed that different doping concentrations in the polysilicon could lead to different voltage and temperature coefficients of the resistor [8–10]. However, there is no enough physical explanation or further analysis for this phenomenon, which is very important for guiding the mass production. On the other hand, circuits for DC-DC and AC-DC applications in the smart power management system

require the resistor to behave robustly under high voltages. This topic is not experimentally studied yet.

In this study, we investigate the voltage and temperature coefficients of polysilicon resistors with different doping concentrations. Secondly, the breakdown voltages (V_{BD}) of the resistors with different sizes are discussed. Also, the impacts of the high and low voltage stresses on the resistance of the polysilicon are experimentally studied. The results show that the voltage and temperature coefficients strongly depend on the doping concentration. After the high voltage stress, the resistance of the polysilicon could be degraded.

2. Experimental

The polysilicon resistors with different doping concentrations were prepared at 1 μm BCD standard process platform. The doping concentrations and corresponding square resistances are summarized in Table 1. Except for the doping concentration, all other processes were the same for all the resistors. The test structure for measurements in this study is shown in Figure 1.

TABLE 1: Doping concentrations and corresponding square resistances at room temperature.

	High	Medium	Low
N-type doping concentration (cm^{-3})	$2E20$	$1.9E19$	$1.5E19$
Resistance at room temperature (ohm/sq)	350 ± 70	2000 ± 400	10000 ± 4000

FIGURE 1: (a) Layout and (b) cross section of the resistor (color online).

FIGURE 2: (a) Resistance-voltage and (b) resistance-temperature curves of three resistors with different resistances (color online).

FIGURE 3: Illustration of the energy band of (a) low doping and (b) high doping concentrations.

FIGURE 4: V_{BD} versus length of the resistor ((a) and (c)) and square of V_{BD} versus the inversed width of the resistor ((b) and (d)) (color online). (a) and (b) come from lightly doped resistors while (c) and (d) come from highly doped ones.

The voltage and temperature coefficients were extracted in the high voltage (< 80 V) region and under the temperature varied from -40°C to 150°C .

V_{BD} of the polysilicon resistors with different widths (W) and lengths (L) were measured. Some polysilicon resistors were electrically stressed with a low voltage (6 V) or a high voltage (80 V) for some time.

3. Results and Discussion

3.1. Resistor Characteristics. Figure 2 shows the voltage and temperature coefficients of the polysilicon resistors with different doping concentrations. All the resistances in Figure 2(b) are obtained with applied voltage of 0.05 V. It could be found from the figure that the resistor with a

relative high doping concentration shows a positive voltage coefficient and a positive temperature coefficient while the other two resistors with much lower doping concentrations have negative voltage and temperature coefficients.

The possible reason for this phenomenon might be as follows. Polysilicon consists of many large grains, which are surrounded by grain boundaries. When the polysilicon is doped with a low impurity concentration, most of the carriers are absorbed by the grain boundaries, resulting in potential barriers around the boundary which could prevent the carriers moving (Figure 3). When a voltage is applied to the resistor, the carriers own a high energy and could more easily travel across the barrier, generating larger current and lower resistance. Similarly, a high temperature could help the carriers across the grain-boundary-induced barriers. Thus, the polysilicon resistor with a lower doping concentration has negative voltage and temperature coefficients. When the polysilicon is heavily doped, the grain boundaries have been full of constrained carriers while there are still many carriers remaining in grains. In this case, there will be little or even no grain-boundary-induced potential barriers around the boundary, while the high voltage and high temperature could cause large scattering within the crystalline grain, resulting in a larger resistance. Thus, the polysilicon resistor with a relative high doping concentration has positive voltage and temperature coefficients.

Therefore, it could be possible for us to make the voltage and temperature coefficients as small as we want if we tune the doping concentration carefully.

3.2. Reliability Behaviors of Polysilicon Resistors. Breakdown voltages of polysilicon resistors with different sizes (W and L) are shown in Figure 4. We can see that the breakdown voltage is proportional to the length of the resistor, while the square of the breakdown voltage is reversely proportional to the width of the resistor. This result is in good agreement to Scaff's research [11] on thermal conductance of a rectangular resistance on an oxide film over a Si substrate. The breakdown voltage decreases with the increase of the width of the resistor in Figure 4, showing that the polysilicon resistor is thermally breakdown, instead of electrically breakdown.

Furthermore, to study the reliability behaviors of the polysilicon resistors under high voltage applications, the same resistors with high doping concentrations were electrically stressed at 6 V and 80 V. As shown in Figure 5, the stress of 6 V has no significant effect on the resistance, while the 80 V stress leads to a quick decrease and then a smooth increase in the resistance of the resistor. We think that the resistance decrease is due to the charge release from the grain boundaries while the increase could be attributed to self-heating of the polysilicon.

The above results suggest that, in order to ensure that the resistor behaves robustly in the circuits, the study on the breakdown voltage of the resistor with different sizes is required. Besides, the voltage stress should be a necessary item for the reliability evaluation including both self-heating and electromigration effects of polysilicon resistors [12–16].

FIGURE 5: Normalized resistance under 6 V and 80 V stress (color online).

3.3. New Structure Proposal for Resistor due to Oxide Consideration. According to the structure of resistor in Figure 1, we can see that if the voltage application of the resistor comes up to several hundred volts, the voltage across the oxide is several hundred volts and the electrical field density is above the critical density of breakdown of silicon dioxide (Figure 6(a)). On the other hand, a high voltage on the resistor has a simultaneous vertical electrical field which may lead to a lot of reliability problems of the oxide for isolation. Thus, oxide breakdown becomes another shortcoming for high voltage application of resistor. A new structure in Figure 6(b) is suggested for the resistor to add a lightly doped N-type well under the oxide if the substrate is P-type doped. In this way, a PN diode is formed below the oxide. When high voltage is stressed on the resistor, the diode is reversed biased and undertakes parts of the voltage. The whole structure can be summarized as an oxide capacitance and a diode in series in Figure 6(c). We can see that the breakdown voltage of the vertical structure [11, 12] can be increased and the voltage stressed on the resistor can be increased.

4. Conclusions

We have experimentally investigated the voltage and temperature coefficients of polysilicon resistors for high voltage applications. The experimental results show that ultralow voltage and temperature coefficients (~ 0) could be achieved according to carefully tuned doping concentrations. We also found that the breakdown of the polysilicon resistors under a high voltage is a thermal-dominant process, rather than an electrical process. Furthermore, the high voltage stress can degrade the performance of the polysilicon.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

FIGURE 6: (color online) (a) Simplified vertical structure for resistor (b) added Nwell beneath the oxide to raise the breakdown voltage of the vertical structure.

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