SIMULATION OF SEMICONDUCTOR DEVICES AND PROCESSES Vol. 6
Edited by H. Ryssel, P. Pichler - September 1995

Effect of Process-Induced Mechanical Stress on Circuit Layout

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Abstract

The effect of process-induced mechanical stress on characteristics of a simple differential amplifier circuit are analyzed using the finite element method, based on the piezoresistance effect of diffused resistors and the experimentally determined sensitivities of transistor characteristics to stress. The predicted change distribution of the resistivity of p-type diffused resistors and of the h_{fe} and V_{be} of pnp transistors agree well with the measured data.

1.Introduction

With the trend towards high integration of LSIs, device structures have been becoming increasingly complicated, and the number of thin–film materials used has been increasing. These structural changes have caused mechanical stress to increase in device structures. The stress developed is sometimes high enough to cause not only mechanical failures such as dislocations in silicon substrates and cracking or delamination of thin films, but also electronic ones. Thus, it is increasingly important to evaluate and control the mechanical stresses in the device structure in order to improve product reliability.[1)]

Recently, deep isolation structures have come to be used for bipolar devices. An isolation structure is formed using the local thermal oxidation of silicon (LOCOS) process. The thickness of the newly grown oxide film reaches about 2 µm. Great stress is generated near the Si/SiO_2 interface during thermal oxidation, because of volumetric expansion of the newly oxidized film.[2)] Passivation films such as SiO_2 and Si_3N_4 also have high intrinsic stress, and thus change the stress fields in silicon substrates.

Since the resistivity of diffused resistors and the electronic performance of transistors are changed by mechanical stress[3)-6)], these process-induced stresses sometimes cause serious damage to circuit performance. An example of this is a carrier–signal leakage failure that occurred in a simple differential amplifier circuit (Fig. 1) located near a thick oxide film. The failure mechanism was analyzed with respect to the change in circuit performance due to process-induced mechanical stress.

2. Stress Simulation

Mechanical stress fields in device structures were analyzed using the finite element method. Both stress-dependent oxidation and the intrinsic stress of thin films were taken into account.[7)8)] Figure 2 shows an example of the predicted residual stress distribution of normal stress σ_x after the LOCOS process. Stress concentrates at the Si/SiO_2 interface. A stress field develops within an area about 10 μm from the oxide edge. The stress distribution at the silicon–substrate surface is summarized in Fig. 3 The normal-stress component σ_y and shear–stress component τ_{xy} are relatively small, and exist only within 5 μm of the edge. On the other hand, the normal stress σ_x shows a highest value of about 600 MPa at 1 μm from the edge and decreases monotonically to almost zero at 15 μm from the edge.

These stress distributions are slightly changed due to passivation–film stress. Figure 4 shows the effect of the passivation film on the distribution of the residual normal stress (σ_x) at the substrate surface. When a PSG film was used for passivation, the compressive stress developed due to oxidation decreased by about 30% near the oxide edge. This was because the film had a tensile stress of about 200 MPa. On the other hand, the compressive stress increased when a silicon-nitride (P-SiN) film was used for passivation. This increase was due to the compressive stress of about 400 MPa of the nitride film. Therefore, the selection of material for the passivation film is also an important factor in mechanical stress control for silicon substrates.

3. Device–characteristic changes caused by mechanical stress

Device–characteristic changes were analyzed considering the piezoresistance–effects and experimentally determined stress sensitivities of transistor characteristics. The resistivity change of diffused resistors was calculated using the following equation:

$$dR/R = [\iint\{S_j p_{ij} \sigma_j\}^{-1} dxdy]^{-1} ,\ (j=1\cdots 6,\ i=1\cdots 6)$$

Where, R is resistivity, p_{ij} is the piezoresistance coefficient[6)], and σ_j is three dimensional stress component. The integration was performed on a diffused resistor area 1 μm wide and 0.1 μm deep. The calculated distribution of the resistivity change of the p-type diffused resistors is shown in Fig. 5 (measured results are also shown in this figure). The maximum change, of about 1%, was predicted at 2 μm from the oxide edge, and the measured value agreed well with this prediction. The change rate decreases monotonically to almost zero at 15 μm from the edge. The measured change rate of about 0.1% at 10 μm from the edge also shows good agreement with the predicted result.

The characteristic changes of bipolar transistors such h_{fe} and V_{be} were predicted based on the results of stress simulations and their experimentally determined stress sensitivities. The stress sensitivities were measured by applying mechanical stress to the transistors using a four-point bending test of strips cut from the device-fabricated silicon wafers. The values obtained for the pnp transistor were about 7%/100 MPa for h_{fe} and 3.5mV/MPa for V_{be}. The change distributions of h_{fe} and V_{be} predicted for the pnp transistor are shown in Fig. 6. Both of these characteristics also changed near the Si/SiO_2 interface. The h_{fe} and V_{be} decreased about 10% and 20 mV, respectively, at 2 μm from the edge. Both changes decreased monotonically to almost zero at 15 μm from the edge, as the resistivity change did. These predictions agreed well with the measured data.

Similar predictions were made for n-type diffused resistors and an npn transistor. The predicted resistivity change of the n-type diffused resistors is shown in Fig. 7. In this case, resistivity decreased by about 10% at 2 μm from the oxide edge. This rate of change was about ten times as high as that of p-type diffused resistors. Thus, we can see that the resistivity of n-type diffused resistors is more sensitive to mechanical stress than that of p-type diffused resistors. From this point of view, p-type diffused resistors should be used in the high stress areas to minimize the resistivity change. Figure 8 shows the predicted changes of the h_{fe} and V_{be} of the npn transistor. The h_{fe} increased by about 10% at 2 μm from the oxide edge. Though the sign of the change was the opposite, the change rate was almost same as that of a pnp transistor. The V_{be} change was about 20 mV at 2 μm from the oxide edge, which was also almost same as that of the pnp transistor. Thus, the absolute values of the stress sensitivities of h_{fe} and V_{be} for the npn transistor were almost same as those for the pnp transistor.

Some precise differential amplifiers require resistivity changes less than 0.1%. These circuits must be located more than 10 μm away from the oxide edge. This limitation can change because the stress distribution varies with the oxide film thickness and the thickness and materials of passivation films. These process parameters are important factors for mechanical stress control and thus for the improvement of device reliability. Our stress simulation is effective for the optimization of device structures and circuit layout to improve device reliability.

4. Summary

The mechanism of change of the device characteristics of a simple differential amplifier circuit located near a thick thermally oxidized film was analyzed by applying the finite element method, taking process-induced mechanical stress into account. The characteristic changes were predicted based on the piezoresistance effect of diffused resistors and the experimentally determined stress sensitivities of transistor characteristics. The predicted distribution of resistivity change of p-type diffused resistors and changes of the h_{fe} and V_{be} of a pnp transistor agreed well with the measured data. Therefore, mechanical stress simulation is clearly an effective way to design circuit layouts in consideration of performance changes due to process-induced mechanical stress.

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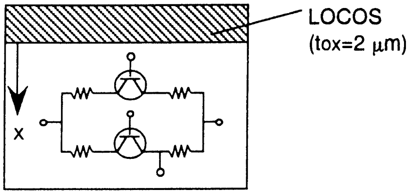

Fig. 1 A differential amplifier located near thick LOCOS

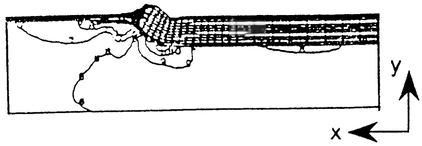

Fig. 2 Predicted stress distribution in the silicon substrate after local thermal oxidation

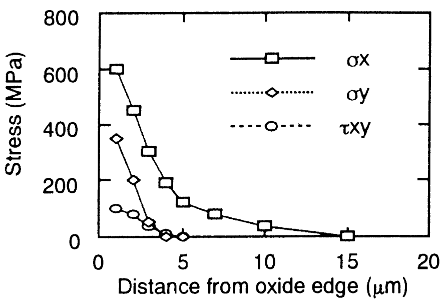

Fig. 3 Stress distribution at silicon substrate surface near thick LOCOS edge

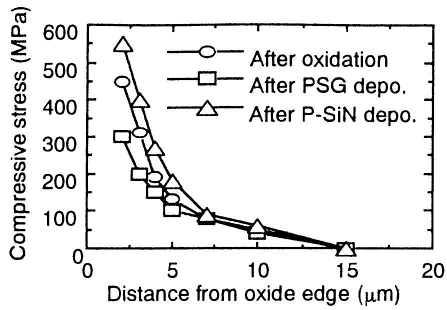

Fig. 4 Effect of passivation film on the residual stress at the silicon substrate surface

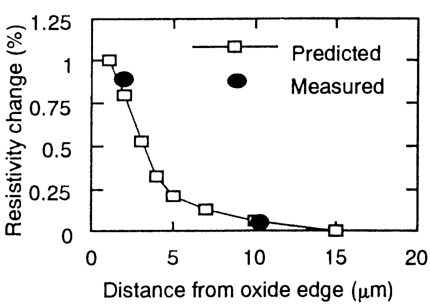

Fig. 5 Comparison of predicted resistivity changes of diffused resistors with measured changes

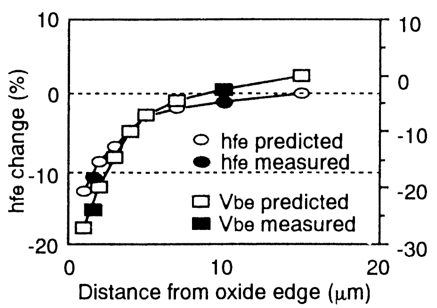

Fig. 6 Comparison of predicted changes of hfe and Vbe of a pnp transistor with measured changes

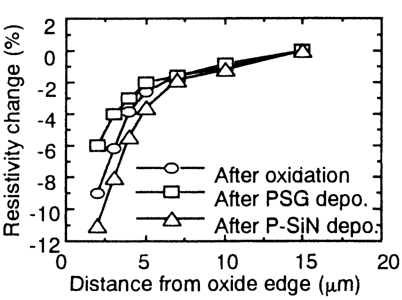

Fig. 7 Predicted resistivity changes of n-type diffused resistors

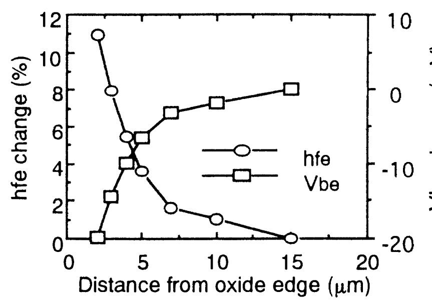

Fig. 8 Predicted changes of hfe and Vbe of an npn transistor