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Analysis of structural effect on mechanical stress at backside deep trench isolation using finite element method

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ABSTRACT

BDTI (backside deep trench isolation) structures parallel to a depth direction of a Si wafer may generate a stress concentration under the warpage caused by a mechanical loading on the wafer during handling or moving. Our work aims to provide a better understanding for minimizing a stress concentration effectively at the BDTI. To address shape factors of the BDTIs with a void, we change δ (open width), $\boldsymbol{d}_{\mathrm{BDTI}}$ (distance between Si-surface and BDTI bottom), θ (angle between Si-surface and sidewall of BDTI), and $\boldsymbol{t}_{\mathrm{1st\ HfOx}}$ (thickness of 1st HfO_x film on silicon surface). Among the geometrical factors changed in this work, our simulation predicts that the opening length and the thickness of 1st HfOx films are key factors to control a maximum stress concentration at a 1st HfOx film below an oxide bottom. Comparing only a final geometry of various BDTIs, it is consequently very effective to decrease the interface curvature between an HfO_x and oxide films in order to get low stress structures.

1. Introductions

Demand of high-resolution CMOS image sensors keeps increasing in various industries and applications such as mobile phones, digital cameras, and car safety systems. To get a better sensor performance in continuously shrinking of pixel sizes, a backside illumination (BSI) has been preferred to a front side illumination (FSI) [1–3]. Besides, deep trench isolation (DTI) is known to reduce effectively a pixel crosstalk [4–6]. Particularly a backside deep trench isolation (BDTI) is favorable, due to its excellent quantum efficiency, in high-resolution CMOS image sensors [1,5]. Even though the crosstalk at very small size pixels still exists, however, in spite of using the BDTI [1]. Nevertheless, a technology associated with the BDTI is very attractive at pixel size of <1.12 μm.

The BDTI structures parallel to the depth direction of a Si wafer may introduce a stress concentration under the warpage caused by mechanical loading on the wafer during handling or moving. If the stress concentration is larger than fracture stress of silicon, a crack occurs from the BDTIs, and reliability gets damaged seriously.[8,9]. While previous works about the BDTI or DTI have focused on its performance as an image sensor like cross talk and leakage current, [4–7] such a mechanical reliability has never been addressed at the BDTI. We study the structural stability of the BDTI on the basis of a mechanical stress analysis using a TCAD simulation here. Basically a stress distribution by a shape of the BDTI is investigated under an applied displacement with a couple of factors: width, depth and Si-etching angle. We also examine a thickness effect of thin films on the stress of the BDTI.

As a pixel size decreases for high integrity in CMOS image sensors, possible mechanical failures, such as a crack and a fracture, as well as a device performance will need to be carefully considered due to using more BDTIs. The role of our work is to provide a better interpretation on minimizing the stress concentration effectively at the BDTIs. Furthermore, our stress analysis will stimulate other researchers who want to get an insight of how the stress field resulted from the BDTI is indeed related to electrical components to overcome like leakage or dark current.

2. Simulation approach

The 'Sentaurus interconnect' of 'Synopsys' is used for TCAD simulation based on the finite element method (FEM). Simulation cells of rectangular parallelepiped (1 μm × 1 μm × 2 μm) including a BDTI are illustrated in Fig. 1(d). The BDTI structure before forming a Si-lens and color filters is prepared in this work without any front end of line (FEOL) process. To consider stress situation corresponding to real warpage in our simulation, the displacement of 0.5 nm is applied to outside of cell boundary normal to the x-direction in the BDTI as shown as red arrows (u_x) in Fig. 1(d). A stress simulation is conducted with a free boundary condition on a top side and fixed boundary conditions on the other five sides in the simulation cell. During simulation processes of etching and deposition, the stress of corresponding materials is relaxed. On the other hand, a stress history is stored with

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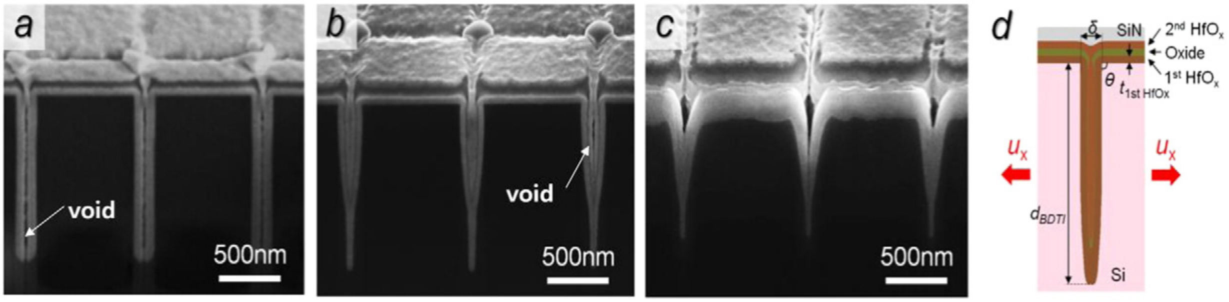

Fig. 1. 2D cross-sectional views of real and simulation BDTI structures. (a), (b) and (c) indicate different types of BDTIs. (d) a schematic of simulation structure. $\boldsymbol{d}_{\mathrm{BDTI}}$: distance from a silicon surface to the lowest point of 1st HfO_x as a depth of the BDTI, δ: width of the BDTI, $\boldsymbol{t}_{\mathrm{1st\ HfOx}}$: thickness of 1st HfO_x and θ: angle between a silicon surface and a side wall of the BDTI. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Material parameters for our FEM simulation.

Material	E/GPa	γ	CTE/°C	$\sigma_{\mathrm{intrinsic}}$/MPa
Si	122.7	0.28	3×10^{-6}	–
HfOx	283.6	0.299	8.5×10^{-6}	–
Oxide (SiO_2)	71.	0.16	1.37×10^{-6}	–
Ti	106	0.34	8.6×10^{-6}	–
TiN	251	0.25	9.35×10^{-6}	–
W	411	0.28	4.5×10^{-6}	1000
SiN	310	0.27	3.3×10^{-6}	−75

E: elastic modulus, γ: poison ratio, CTE: coefficient of thermal expansion and $\sigma_{\mathrm{intrinsic}}$: intrinsic stress.

a consideration of intrinsic stress and thermal stress caused by thermal coefficient mismatch during deposition of films. Intrinsic stresses of nitride and tungsten experimentally measured for this work are applied with −75 MPa and 1 GPa to both x- and y-directions, respectively. Table 1 summarizes the material parameters and conditions adopted in this simulation.

The deposition temperature in our simulation is as follows. After 1st HfO_x and SiO_2 films are deposited at 270 °C and 27 °C, the cell is annealed at 350 °C. The deposition temperature of 2nd HfO_x and SiN on a surface of the SiO_2 film are 270 and 350 °C, respectively. After Ti, TiN and W films are formed on the oxide film at 27 °C, a SiN film is deposited at 350 °C. All stress analyses are carried out at 27 °C.

3. Results & discussions

Our BDTIs experimentally formed on silicon wafers were found to be a source of crack under some situations. Even though a main stress resulted in the crack obviously came externally, it is significant to know residual stress ($\sigma_{\mathrm{residual}}$) distribution at and near the BDTIs [10]. The $\sigma_{\mathrm{residual}}$ may be also obtained from an intrinsic stress ($\sigma_{\mathrm{intrinsic}}$) which exists in spite of no temperature change ($\Delta T = 0$) during deposition and a thermal stress ($\sigma_{\mathrm{thermal}}$) at $\Delta T \neq 0$ by a mismatch of thermal expansion coefficients between two heterogeneous materials [11]. Thus, we first observe the BDTI stress produced by $\sigma_{\mathrm{intrinsic}}$ and $\sigma_{\mathrm{thermal}}$ of each film before investigating an effect of applied stress.

Mechanical failures often occur owing to a high intrinsic stress. A tungsten (W) film has the highest intrinsic stress (~1 GPa) among thin films consisting of the BDTI and its upper structure. To investigate its effect on the BDTI, stress distributions before and after W deposition are shown in Fig. 2. The W film is seen as red color on a Ti film, top surface of Fig. 2(a), and in Fig. 2(b) owing to its high tensile stress. Comparing Fig. 2(a) and (b), a lateral stress locally increases at Ti/TiN and SiN after deposition of the W film. However the σ_{xx} difference between Fig. 2(a) and (b) becomes smaller after patterning the W film in Fig. 2(c). The HfO_x film first coated at a deep silicon trench shows high tensile stress even before deposition of the W film. On the other hand, there is no obvious change in σ_{zz} as presented in Fig. 2(d), (e), and (f). It thus appears as if residual stress on a lower structure of the BDTI from deposited W film is insignificant.

The BDTIs show various shapes by their process conditions as shown in Fig. 1(a)–(c). Besides, an elliptical void is sometimes created inside the BDTI. It is interesting to understand a formation and a mechanical stress of the void structure. In forming the void inside the BDTI an etched Si trench should have basically a high aspect ratio ($\boldsymbol{d}_{\mathrm{BDTI}} \gg \delta$) to enable a selective deposition by a conformality difference. An opening of the BDTI becomes narrow without filling inside by typical CVD deposition of an oxide film with comparatively lower conformality

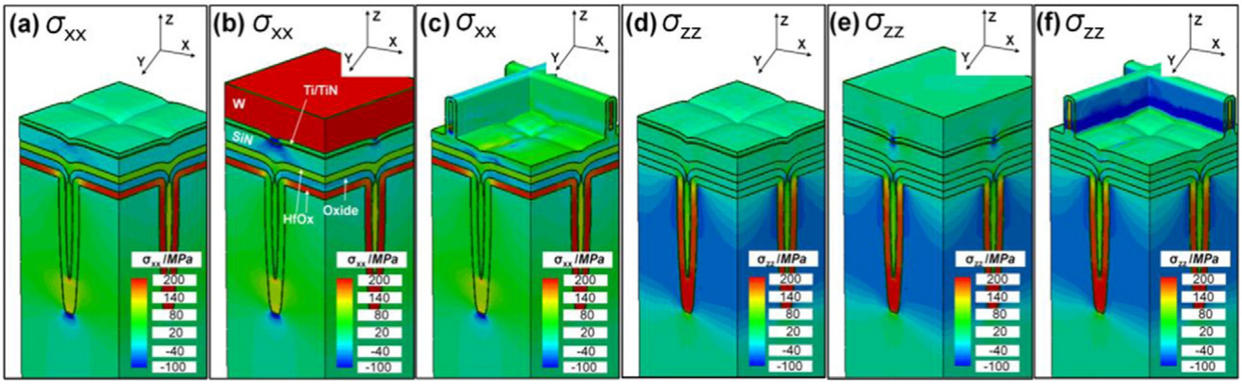

Fig. 2. Stress distribution of BDTI and its upper structure during depositing W film. (a)–(f) indicate a distribution of principal stress of σ_x (a, b, c) and σ_z (d, e ,f) before (a, d) and after (b, e) W deposition, and after W patterning (c, f).