Ageing mechanisms in Deep Trench Termination (DT²) Diode

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Thermal cycling induces delamination and causes cyclic strains in a similar way to natural usage and weakens the normal functioning by thermal fatigue. Therefore, such approach can be conveniently used in accelerated testing of components to assess their reliability. The purpose of this work is to evaluate the reliability of DT² diode, by accelerated ageing process. Two major modes of failure were observed: the first one is the delamination of the chip and the second one concerns the breakdown voltage variation. Optical observations as well as Scanning Electron Microscopy (SEM) analysis have shown a delamination around the trench termination. Finite element simulations are carried out to explain the experimental results and justify the breakdown voltage variation.

1. Introduction

In the past, strong research efforts have been devoted to the investigation of innovative termination techniques for high voltage devices. Indeed, it is necessary to create an adequate edge termination to reduce the electric field peak at the device periphery.

Several techniques have been proposed to improve the voltage handling capability of high voltage power semiconductor devices. Floating guard rings [1], field plates [2], semi-resistive layers like Semi-Insulating Polycrystalline Silicon (SIPOS) [3], Junction Termination Extension (JTE) [4] and 3D RESURF [5,6], have become representative techniques for high voltage power semiconductor devices. However, these techniques need large area and/or elaborate additional process steps.

To overcome such drawbacks of the conventional technologies, the trench termination [7,8] is considered as a very attractive alternative solution to improve the breakdown voltage and reduce the termination area compared with the conventional structure.

In 2008, the first Deep Trench Termination (DT²) diode was fabricated. Electrical measurements and experimental results have demonstrated the efficiency of this technology [9] and then, several studies [10,11] have proposed electrical improvements.

The 3D cross sectional view of the Deep Trench Termination diode is shown in Fig. 1. This new junction termination is based on a large and deep trench (105 μm × 72 μm) filled by BenzoCycloButene (BCB), associated to a field plate which is needed to draw out the electrostatic potential in the trench. The dimension and the doping layers of the DT² diode are indicated in Table 1.

Together with the evolution of the Deep Trench Termination technology, investigations of the degradation of these components become a priority. The aim of this work is to study the ageing mechanisms of DT² diodes. Optical observations and Scanning Electron Microscopy (SEM) analysis have demonstrated the presence of delamination around the trench termination. Finally, we propose to use finite element simulation to justify the electrical variations that can be observed after passive thermal ageing. Several degradations have been implemented in the simulated structure leading to a better understanding of the ageing mechanisms.

2. Thermal ageing

As a first step, diodes coming from the same wafer were reported on substrates using silver sintering process to prevent from failure linked to the die-attach degradation under ageing. DBC (Direct Bonded Copper) substrates with gold metal substrate finishes (Cu/Ni/Au) were used as presented in Fig. 2. The pads were connected to the chip via aluminium wire bondings for anode contact, and via gold metal for cathode contact.
The first assemblies using silver sintering process were successfully realized, and no void can be observed along the trench after the process. Then, considering the device in operation and under various mission profiles, the temperature swings can induce various failures as pointed out in [12]. Temperature cycling and power cycling tests represent these conditions. Therefore, to simulate the real application, passive power cycling tests are the most commonly used in the qualification procedure for components.

2.1. Experimental approach

A climatic chamber with two independent rooms has been used for thermal cycling. Temperature has been set up to two specific values and no bias is applied during thermal cycling. In this study, standard temperature profile has been set up: a high temperature value of +125 °C and a low temperature of −40 °C are fixed.

The passive thermal cycling test was stopped every 100 thermal cycles. The samples were then removed from the climatic chamber, and the I–V reverse characteristics were achieved with the help of the power pulse curve tracer TEK371A. Two main behaviours of DT2 diode were found, despite they have the same manufacturing process. Fig. 3 presents the evolution of the breakdown voltage according to the cycling time of two series of DT2 diodes. The Series 1 diodes show a decrease of the breakdown voltage, whereas an increase is depicted for the Series 2. Together with the breakdown voltage variation, delaminations have been observed on the top view of the dice. To understand this behaviour, optical and Scanning Electron Microscopy (SEM) observations are required.

2.2. Optical and Scanning Electron Microscopy observations

Samples were prepared for optical and Scanning Electron Microscopy (SEM) observations, in order to observe the exact place of delamination in the chip. Fig. 4(a) and (b) depicts a delamination at the silicon/BCB interface in the non-metallization side and in the gold metallization side respectively.

Fig. 4(c) presents a delamination at the interface Si/BCB in the gold metallization side. It can be observed that the gold metallization has not been broken. We have also noted that the diode presents a delamination located in the trench termination. Indeed, geometric singularities and various mechanical properties of BenzoCycloButen (CTE = 42 ppm/°C) [13] and silicon (CTE = 3 ppm/°C) weaken the chip. Furthermore, it could be due to the stress relieving strengthening in the BCB during the transition from high temperature to low temperature room during thermal ageing.

Despite the optical observations and SEM analysis, it is not possible to confirm that delamination can be responsible for the breakdown voltage variations, and hence, more investigations are definitely requested. Therefore, a simulation approach is proposed.

3. Finite element simulation

3.1. Delamination modelling

In order to illustrate the effect of delamination at the Si/BCB interface and to have a better understanding of the breakdown voltage of the device, 2D physical finite element simulations have been performed with TCAD SENTAURUS software [14].

At the Si/BCB interface, voids with various sizes have been implemented to observe their impact on the reverse characteristics. These voids were created at the internal Si/BCB interface or at its external one, with or without electrode crack (Fig. 5).
In the simulation approach, the following assumptions have been made based on the optical observation: The delamination is homogenous and perpendicular to the anode contact; the crack is local, so the gold plate is not fully disconnected (Case b).

The simulation results for all cases illustrate that a separation at the interface does not affect the breakdown voltage.

The insertion of a void in the structure at the interface Si/BCB modifies the distribution of potential lines due to the low permittivity of the void (Fig. 6(a) and (b)). This variation does not affect the breakdown voltage of the structure. This can be explained because the electric field is concentrated at the end of the field plate and does not induce change in this area.

This change creates a local increase of the electric field, but remains very low and has no impact in the breakdown voltage of the structure. Fig. 6(c) depicts the impact of the void created in the structure on the electric field along a horizontal cut-line (EE').

Delamination can be considered as failure indicator, but it does not explain the breakdown voltage variation. Therefore, it can be concluded that with a separation of materials due to mechanical stress resulting from thermal variations, fixed charges may appear at the Si/BCB interface.

3.2. Interface charge modelling

The insertion of positive electric charges in the Si/BCB interface creates a virtual P+/N− junction along the trench. However, the insertion of negative electric charges in the Si/BCB interface creates a virtual N+/N− junction along the trench [15]. Fig. 7 represents the fixed charge effect on the reverse characteristic.

The breakdown voltage is modified by charges insertion at the Si/BCB interface. The simulations highlight that the device is sensitive to fixed charges.

In order to understand the effect of charges on the breakdown voltage, a first comparison is made between two doses of charge with holes and a second with electrons (see Fig. 7).

Fig. 4. Optical and SEM observations of delamination at the interface Si/BCB (a) in the non-metallization side and in the gold metalized side (b) with crack, and (c) without crack of the gold.

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3.2.1. Negative charge

The two proposed doses are $C = -1 \times 10^{10}$ cm$^{-2}$ and $C = -4 \times 10^{12}$ cm$^{-2}$. Fig. 8 depicts the 2D potential line distribution in the structure.

For a dose of $-1 \times 10^{10}$ cm$^{-2}$, the breakdown voltage is equal to 1294 V, all potential lines are spread throughout area 1. In fact, the depletion is not modified by the fixed charges and is spread along 120 μm, such as in a structure without injected fixed charges. All the electrons injected are recombined with holes, enabling the potential lines to be spread in the termination depth. Besides, for a dose of $-4 \times 10^{12}$ cm$^{-2}$, the breakdown voltage is equal to 25 V, all potential lines are stuck and concentrated in area 2. Indeed, there are just some injected electrons at the interface Si/BCB which are recombined with holes.

To have a better understanding the premature breakdown causes, a comparison of the electric field distribution in the structure for two doses of charges is made for a constant voltage.

Fig. 9 presents a snapshot of electric field at 25 V, and a horizontal cut line (AA') for the two chosen doses. The concentration of potential lines in area 2 has created a local increase of electric field, causing so a premature avalanche in the structure. The horizontal cut line has enabled to determine the localisation of electric field peak (area 2).

The increase of electric field has an influence on the current distribution. Fig. 10(a) and (b) shows the current distribution in the structure at 25 V. Fig. 10(a) points that for a low dose, the current distribution is homogeneous in the structure, while for a high dose (Fig. 10b), the current is concentrated along the Si/BCB interface and more important than for a dose of $-1 \times 10^{10}$ cm$^{-2}$ (Fig. 10c), so the structure can be degraded by self-heating.

3.2.2. Positive charges

The two proposed doses are $C = +1 \times 10^{12}$ cm$^{-2}$ and $C = +5 \times 10^{12}$ cm$^{-2}$. Fig. 11 depicts the 2D potential line distribution in the structure.

For a dose of $+1 \times 10^{12}$ cm$^{-2}$, the breakdown voltage is equal to 1555 V. Indeed, all holes are recombined with electrons. Thus, the potential lines are propagated inside depth termination. While, for a dose of $+5 \times 10^{12}$ cm$^{-2}$, the breakdown voltage is equal to 254 V. The potential lines cannot enter inside the trench, remain around him and concentrate in its corners. Indeed, there are just some holes which are recombined with electrons, and the others are remained stuck at the interface.

In order to identify the premature breakdown region, a snapshot of electric field in the corners trench is recorded at 254 V (Fig. 12(a) and (b)).

Fig. 5. Schematic cross-section of the various placements of the delamination. (a) Internal side without anode crack, (b) internal side with anode crack and (c) external side.

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The concentration of potential lines at the trench corners created a local increase of electric field, the abrupt increase has developed a premature breakdown.

The horizontal cut line in the trench bottom (Fig. 12(c)) shows the existence of two electric field peaks at the corner trench for the high dose structure. For this reason, such structure can only support a lower voltage (254 V) compared to the structure having a low dose (1555 V).

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**Fig. 6.** Potential lines distribution in the structure and its zoom (a) without and (b) with delamination, (c) electrical filed along the horizontal E-E’ cut-line.

**Fig. 8.** 2D potential line distribution in the structure for a dose of (a) \( C = -1 \times 10^{10} \text{ cm}^{-2} \) and (b) \( C = -4 \times 10^{10} \text{ cm}^{-2} \).

**Fig. 9.** 2D electric field distribution for a dose of (a) \( C = -1 \times 10^{10} \text{ cm}^{-2} \) and (b) \( C = -4 \times 10^{10} \text{ cm}^{-2} \), (c) representation of the electric field distribution along the A-A’ horizontal cut-line.
3.2.3. Discussion

The difference between Series 1 and 2 is explained by the type and the dose of charges generated at the Si/BCB interface during thermal ageing. Then, for Series 1 of DT² diodes, the decrease of the breakdown voltage can be explained by a high quantity of positive fixed charge or negative fixed charge created at the interface. For the Series 2 behaviour can be explained by the low quantity of positive fixed charge created at the interface.

Fig. 10. 2D current density distribution for (a) $C = -1 \times 10^{10}$ cm$^{-2}$ (b) $C = -4 \times 10^{12}$ cm$^{-2}$, (c) representation of current density distribution along the B-B’ vertical cut-line.

Fig. 11. 2D potential lines distribution in the structure for a dose of (a) $C = +1 \times 10^{12}$ cm$^{-2}$ and (b) $C = +5 \times 10^{12}$ cm$^{-2}$.
4. Conclusion

This work points out the reliability of DT² diodes in order to be able to reach conclusions on its lifetime under ageing cycle. The reverse characteristics were changed after 400 h of thermal cycling. Optical and Scanning Electron Microscopy (SEM) observations have shown a delamination in a part of the trench termination. With the help of TCAD Sentaurus tools, it has been demonstrated that a delamination has no effect on the breakdown voltage, and the evolution can be explained by fixed charges created at the Si/BCB interface.

In the next work, it will be interesting to find a solution to decrease the effect of fixed charges in the silicon/BCB interfaces.

References


Fig. 12. Zoom of 2D electric field distribution for a dose of (a) $C = +1 \times 10^{12}$ cm$^{-2}$ and (b) $C = +5 \times 10^{12}$ cm$^{-2}$. (c) representation of the electric field distribution along the C–C’ horizontal cut-line.