THE RELATION OF THERMAL DIFFUSION VARIATION TO REVERSE VOLTAGE FOR HIGH POWER DIODE DEVICES

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ABSTRACT

A P-I-N diode is consists of three regions i.e. P-region, intrinsic region an N-region. The P-region and N-region are heavily doped compared to intrinsic region. The depth of the intrinsic region determines the reverse voltage of the diode. Thus, the deeper the depth of the I-region, the higher the reverse voltage produced. This is due to P-I-N diode operates in avalanche breakdown mode. In this paper, we will evaluate the thermal diffusion duration effect to the junction depth of the intrinsic region of a diode. The work includes wafer fabrication of a P-I-N diode, which is subjected to different diffusion times and followed by the measurement of current-voltage characteristic at wafer level. Results show that the longer the thermal diffusion duration, result in shallow intrinsic junction depth. Thus, lowering the reverse voltage.

Keywords: power devices, wafer fabrication, junction depth, reverse voltage.

INTRODUCTION

Semiconductor material has the ability to conduct electrical current in between conductors and insulators (Floyd, 2008). Semiconductor technologies such as diode are formed when a piece of N-type doped silicon merge with P-type doped silicon (Baliga, 1996). An evolution of p-n diode happened when there is an extra lightly dope intrinsic layer formed between p-type and n-type dopants. The PIN diode is one of the very first semiconductor device developed for power circuit applications (Baliga, 1996). Figure-1 illustrates the P-I-N diode structure.

![Figure-1. The PIN diode structure.](image)

P, I and N represents the P-type layer, N-type layer, and intrinsic layer, respectively, that sandwiched between p-type and n-type layer. The P-type and N-type regions are heavily-doped to provide ohmic contact. The intrinsic layer makes this diode ideal for fast switches. Generally, P-I-N diode has very low voltage drop and high breakdown voltage. The depth of the low-doped base region i.e. intrinsic region, define the reverse breakdown of the P-I-N diode. Basically, P-I-N diode is widely used in power electronic applications as their central layer can withstand against high voltage. One of its general applications is protecting electronic circuit against damaged from high voltage. There are a few number of studies for the past decades to explain the behavior of small-signal low power p-n junction diodes (Baliga, 1987; Gandhi, 1977; Hall, 1952; Jubadi & Noor, 2010; Kingston, 1954; Mazhari, Sinha, & Dixit, 2006; Moll, 1964; Pendharkar, Trivedi, & Shenai, 1996; Salah et al. 2007; Sze, 1969; Tsukuda, Sakiyama, Ninomiya, & Yamaguchi, 2009) and high-power P-I-N diode (Abiri, Salehi, Kohan, & Mirzazadeh, 2010; Jablonski, 1998; Sawant & Baliga, 1999; Shuhaimi et al. 2010).

In this paper, a commercially available P-I-N diode is used to investigate the variable depth in I-region on the current-voltage (I-V) performances. Initially, the depth of the I-region is a constant and it can only be changed during diode wafer fabrication. This is due to N+ is the bulk substrate and intrinsic region is the epitaxial layer. Both of epitaxial layer and substrate have a constant depth. A diode is formed when the P+ dopant is diffused into the intrinsic region during wafer fabrication. The diffusion of the P+ dopant into the intrinsic region caused the junction depth of the I-Region to be shortened. Diode formation is formed by diffusing a P+ dopant into intrinsic region. The PIN diode structure is illustrated as in Figure-1, where the junction depth variation (d) is controlled by the depth of P+ impurities dopant formed during fabrication.

Since P-I-N diode operates in a thickness-limited mode, which is, controlled by the depth of an I-region, different depth in P-region during thermal diffusion will lead to different junction depth in I-region. The deeper the junction depth of the P-region, the shallower the junction depth of the I-region. This is because more of the intrinsic region is consumed to form a P-region. Thus, in this work, we tune the depth of the P-region to study the effect of reverse voltage and I-region depth as illustrated in Figure-2.

![Figure-2. Junction depth variable of the intrinsic region is evaluated.](image)
METHODOLOGY

In semiconductor manufacturing field, there is a fixed temperature and diffusion time to form a targeted length of the P-region of the diode. The deeper the junction depth of the P-region, the shallower the I-region due to more intrinsic region depth is consumed to form a P-region. The deeper the junction depth of the P-region, the lower the reverse voltage due to power diode operates in avalanche mode. Figure-3 shows the summarized experimental process flow used in our work. The work includes wafer fabrication of a P-I-N diode, which is subjected to different diffusion times and followed by the measurement of current-voltage characteristic at wafer level.

The process that needs to be evaluated is the P-region formation of a diode. The intrinsic region and N+ region is constant due to they are wafer substrate. Thus, only P-region depth is the remaining variables in wafer fabrication and also the key factor to change the junction depth of the intrinsic region. P-region is formed by diffusing P type dopant into I-region. In this paper, we evaluate three different thermal durations to form a P-region, which are 60 minutes difference between each other. The temperature of the thermal diffusion process remains constant at 1050 °C. Upon completion, the evaluation wafers for each of the thermal duration times were tested for the current-voltage of the diode. The electrical current-voltage data are collected through electrical testing were then analyzed through analytical software. In addition to the electrical testing, we also sent the samples to destructive analysis to validate the hypothesis of this evaluation. The destructive analysis is spreading resistance profiling (SRP) analysis. It is a technique to analyze the resistivity of versus the depth in semiconductor manufacturing.

The evaluations are summarized in process flow Figure-3.

![Process flow diagram](image)

**Figure-3.** The overall process flow of the thermal diffusion evaluation.

The splits evaluation is summarized in Table-1, where the thermal diffusion temperatures remained constant at 1050 °C. We would like to stress out here, the impact of temperature is less dominant than duration times, and therefore only one temperature at the nominal condition is considered. Unlike the thermal duration times that has more dominant and direct impact to the junction depth of the P-region. Thermal diffusion A is the shortest time, C is the longest one, while B lies in between with 60 minutes interval time between them. We expect, the longer the duration time, the deeper the junction depth of P-region will be achieved and thus resulting the shallowness of the I-region.

RESULT AND DISCUSSION

Three different thermal duration splits were electrically measured by using electrical testers. Data from all three splits collected from tester were then analyzed in statistical software. Figure-4 and 5 show the reverse voltage of the diode at different biasing. From the statistical analysis, we can see that, the longer the thermal diffusion time, the lower the reverse voltage. This is due to longer thermal diffusion time formed a deeper depth of a P-region and caused shallower depth of the I-region. Basically, the P-I-N diode operated in avalanche mode. In this operation, the reverse breakdown voltage is controlled by the depth of the I-region. Thus, the longer the P-region diffusion duration (translated into deeper junction depth of P-region), the lower the reverse breakdown voltage a P-I-N diode obtained (due to shallow junction depth of I-region). From this evaluation, the difference of 60 minutes in thermal diffusion time has lowered down the reverse breakdown by 30 V. The reverse voltage and the thermal diffusion time are summarized in Table-1.

**Table-1.** The reverse voltage for each of the split.

<table>
<thead>
<tr>
<th>Thermal diffusion duration at 1050 °C</th>
<th>Reverse breakdown voltage (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal diffusion A, n minutes</td>
<td>300 V</td>
</tr>
<tr>
<td>Thermal diffusion B, n minutes + 60 minutes</td>
<td>270 V</td>
</tr>
<tr>
<td>Thermal diffusion C, n minutes + 120 minutes</td>
<td>240 V</td>
</tr>
</tbody>
</table>

Figure-4 shows the electrical distribution of each split at 2 μA biasing.

![Electrical distribution](image)

**Figure-4.** The reverse voltage (VR) test distributions for all the cells at 2 μA biasing.
We can see that, thermal diffusion time C have the lowest reverse voltage and followed by thermal diffusion time B. The mean value of the thermal diffusion C reverse voltage is at around 240 V. Thermal diffusion A has the highest reverse voltage at around 300 V. Thermal diffusion A has the shortest diffusion duration compared to the Thermal diffusion B and Thermal diffusion C. This result correlates with the shorter the P-region diffusion duration; the shorter the junction depth of the P-region and hence the deeper depth of the I-region. This is why thermal diffusion Time A have the highest reverse breakdown voltage as PI-N diode reverse breakdown is controlled by the intrinsic region.

Figure-5 shows the reverse voltage electrical distribution at higher biasing 10 μA.

![Graph showing reverse voltage distribution for thermal diffusion times A, B, and C.]

**Figure-5.** The reverse breakdown (VR) test distributions for all the cells at 10 μA biasing, with 60 minutes interval between time A, B and C.

We observed the same trend for reverse voltage at higher biasing where thermal diffusion time C have the lowest reverse voltage. Thermal diffusion time C has the lowest reverse voltage compared to other two. This is due to thermal diffusion time C have the deepest P region depth and shallow I-region. Longer diffusion time diffused deeper P junction depth and made a shorter I-region that controls the reverse breakdown of the diode. From the electrical distribution analyzed by statistical software, we can see a difference of around 30 V reverse voltage for each of the splits.

Figure-6 shows the reverse leakage distribution for all the 3 variables. We can see that, the leakage distribution of the variables are statistically comparable.

To validate this evaluation, then we subjected our sample by using spread resistance profiling (SRP) analysis. SRP is an analysis to validate resistivity versus depth of the in semiconductors. Moreover, using SRP analysis can confirm the junction depth of the diode. Figure-7 shows the junction depth of thermal diffusion times A, B and C. The results proved that the hypothesis is true, where the deeper junction depth of P-region will have a lower reverse voltage value.

![Graph showing reverse leakage distribution for thermal diffusion times A, B, and C.]

**Figure-6.** The reverse leakage (IR) test distributions for all the cells at 60 V biasing, with interval 60 minutes between time A, B and C.

The right-hand axis indicates the concentration of the diode profile, while the left-axis indicates the doping concentration. From the graph, we can see all the three diodes have the same resistivity, this show they are using the same dopant to form the junction (black, blue and green). The black graph indicates the diode resistivity of the thermal diffusion A, blue graph indicates the diode resistivity of thermal Diffusion B and green graph indicate the resistivity of diode using thermal diffusion C.

The resistivity of the three diodes is very low at around 0.0001 Ω.cm and gradually increases its resistivity and reach the peak at around 15 μm. The resistivity is then dropped slowly drop and remain constant and started to drop back to 0.001 Ω.cm after 25 μm. From the graph, we can conclude, there are three regions with different resistivity in the diode. From 0 to 15 μm, it is a P-region, from 15 to 25 μm, it is an intrinsic region and 25 μm onwards is the N-region.

SRP analysis also able to reveal the junction depth of diode sample. From the graph, thermal diffusion A have the shortest junction depth and then followed by diode thermal diffusion B and diode thermal diffusion C with the value of 14.5 μm, 15 μm and 15.5 μm respectively. This shows that, each 60 minutes extra of thermal diffusion time in P-region caused the junction depth deeper by around 0.5 μm. Moreover, each 0.5 μm of junction depth difference led to a different reverse breakdown value of 30 V.
In summary, the junction depth of the P-region is inversely proportional to the junction depth of the I-region. The junction depth of the I-region is proportional to the reverse voltage of the diode. The deeper the junction depth of the I-region, the higher the reverse voltage of a diode will be due to the avalanche effect. In this case, diode with thermal diffusion time A has the highest reverse voltage and followed by time B and time C as summarized in Table-2, where, at constant temperature, different thermal duration will process a different voltage range of a diode.

Table-2. The reverse voltage for each of the split.

<table>
<thead>
<tr>
<th>Diode</th>
<th>Thermal diffusion duration</th>
<th>Reverse voltage (mean)</th>
<th>Junction Depth of P-region (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode A</td>
<td>Thermal diffusion A, n minutes</td>
<td>300 V</td>
<td>14.5</td>
</tr>
<tr>
<td>Diode B</td>
<td>Thermal diffusion B, n minutes + 60minutes</td>
<td>270 V</td>
<td>15.0</td>
</tr>
<tr>
<td>Diode C</td>
<td>Thermal diffusion C, n minutes + 120minutes</td>
<td>240 V</td>
<td>15.5</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In summary, through the understanding of the device behavior and by applying a systematic approach to optimize the thermal diffusion time, we can target the desired reverse voltage of a device. This paper has identified the effects of thermal diffusion duration to a diode performance. The electrical data we obtained from electrical testing are analyzed in statistical software to check the voltage difference between each split. Results show that 60 minutes difference in thermal diffusion will result in around 30 V reverse voltage difference. From the evaluation, we can then conclude there is a direct impact between reverse voltage (VR) of a diode with thermal diffusion duration of the P-region.

REFERENCES


