Fast recovery Radiation Enhanced Diffusion (RED) Diode: Palladium versus Platinum

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Power semiconductor device, Bipolar device, Fast recovery diode, Free wheel diode (FWD).

Abstract
Modern power switches require the complementary diodes which are robust at the turn-off of ever higher currents at higher di/dts and supply voltages. A new technology to increase the ruggedness of free-wheeling and clamping diodes, which is based on the radiation enhanced diffusion (RED) of palladium, has been recently developed. In this work, the RED technology of palladium is confronted with that of the platinum. Silicon P-i-N diodes (Vbr = 2500 V, Area = 2 cm², positive bevel, press pack contact) were subjected to the RED of Pd and Pt in the temperature range between 500 and 800 °C to locally control the carrier lifetime and doping profile, if possible. The devices are compared in static (leakage, voltage drop) and dynamic parameters (unclamped low inductance reverse recovery). The RED of Pd is shown to create a low doped P-layer that postpones the dynamic avalanche towards higher line voltages and increases the static breakdown voltage. Platinum does not provide this feature and the lifetime reduction is smaller. While the dynamic parameters of the palladium RED diodes are greatly improved, those of the Pt have much higher maximal recovery current and poor SOA. In spite of the qualitatively similar electronic properties of the Pt and Pd deep levels, the accumulation of Pt in the region with radiation defects is found to differ quantitatively during the RED process in the temperature range 500 – 650 °C. The RED of Pt is therefore evaluated as unsuitable for the local lifetime control using the existing RED process.
Introduction

The diffusion of transition metals for carrier lifetime control [1, 2] steadily attracts our attention thanks to few advantages over the state-of-the-art radiation methods. The prominent metals are both the platinum (Pt) [3] and palladium (Pd) due to a low leakage current and ability to diffuse from a surface layer which can be masked [4].

The existing portfolio of the methods mentioned above was recently extended by the introduction of the radiation enhanced diffusion (RED) of palladium by the radiation defects from helium implantation [5]. This concept has provided a fast recovery diode with both the locally reduced carrier lifetime and a low doped buried p-layer which increases the breakdown voltage ($V_{br}$) and reduces the dynamic avalanche (DA). This was shown experimentally and using a device simulation in ref. [6]. The improvement of the $V_{br}$ and the DA using the buried p-layer was also derived analytically in ref. [7].

Later on, the fully functional RED-Diode was demonstrated at 100 mm wafer [8]. The diode was rated at $V_{br} = 4.5$ kV and using the diameter of 91 mm, the current of 7 kA was safely turned-off at $\frac{di}{dt} \approx 1500$ A/$\mu$s and $V_{dc} = 3200$ V up to 140 °C in the voltage source inverter with IGCT switch. At the same time, the clamp-less operation was demonstrated up to 1.3 kA with $\frac{di}{dt} = 9$ kA/$\mu$s at 125°C. This allows the application of the RED diode in any position of the voltage source inverter with the latest generations of high-power IGCTs.

The RED-Diode with the buried p-layer, which brings the benefits mentioned above, was so far successfully processed only using the palladium [8]. The strong similarities in electronic behavior of the Pd and Pt in silicon (charge state, energy levels in the silicon bandgap, capture cross sections, diffusion mechanism, etc.) [9] indicate that the RED-Diode should be feasible also with the diffusion of platinum. It was actually the platinum, which was used in the first studies of the local lifetime control in power diodes using the RED at low-temperatures [10]. The fact, that the lifetime reduction was found not competitive with that of the well established ion irradiation, has motivated the seeking for a better lifetime killer. As a result, the compensation effect of the palladium giving the low doped buried p-layer was found. Following the initial experiments with the test structures optimized for the characterization of deep levels [11], the RED process was studied in a narrow temperature range around 700 °C. In this paper, the temperature range is extended down to 500 °C on the basis of the experience with the palladium. Direct comparison between the RED of the platinum and palladium takes into account the modification of doping profiles, carrier lifetime and both the static and dynamic device parameters. The presented results are valid for short time annealing with moderate cooling rate.

Experimental

Discrete high-power p-i-n diodes with nominal blocking voltage of 2.5 kV and area of 2 cm$^2$ were processed from 370 μm thick (111) float zone neutron transmutation doped silicon wafers. The junction termination has a positive bevel. The diodes were tested free-floating in the press pack with molybdenum buffers at both sides.

<table>
<thead>
<tr>
<th>Group name</th>
<th>Implantation energy of helium</th>
<th>Implantation dose of helium</th>
<th>Annealing temperature and time</th>
<th>Diffusion source at anode surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt&amp;He</td>
<td>10 MeV</td>
<td>$1.10^{12}$ cm$^2$</td>
<td>500 - 800 °C @ 20'</td>
<td>sputtered 50 nm</td>
</tr>
<tr>
<td>Pd&amp;He</td>
<td>10 MeV</td>
<td>$1.10^{12}$ cm$^2$</td>
<td>350 - 800 °C @ 20'</td>
<td>sputtered 50 nm</td>
</tr>
</tbody>
</table>
Lifetime control and the buried low-doped p-layer were carried out using the RED of platinum and palladium. The parameters are summarized in Tab.1. The annealing times, heating and cooling rates were identical for all devices. No electron irradiation was used.

The anode doping profiles of the diodes prior to the application of the RED process are shown in Fig.1 (see the curve "Original profile"). Notice that the anode junction is at the depth of 50 μm. After the RED of the Pd during the 20 minutes of annealing in a vacuum, the n-base is converted from the n-type to p-type doping up to the end of the helium range (≈ 70 μm). The anode junction moves to the depth about 70 μm. Comparison between the Figs.1a) and 1b) implies that the p-type doping concentration decreases in the n-base with increasing annealing temperature. The optimal combination of relevant device parameters was found around the temperature of 650 °C for which the doping profile in Fig.1b) is shown. At this temperature, there is no obvious change of the doping profile after the RED of platinum. A small modification of the doping profile is visible at 600 °C at the helium end of range (see Fig.1a) and it can be found more pronounced down to lower temperatures (not shown here). The qualitative deviation from the palladium is that the n-type doping concentration decreases without the conversion to a p-type doping. This change resembles that of an incomplete annealing of the radiation defects from the implantation of light ions.

![Fig. 1a): Spreading resistance profile of the original diode and after the RED of the Pd and Pt at 600 °C.](image1a)

![Fig. 1b): Spreading resistance profile of the original diode and after the RED of the Pd and Pt at 650 °C.](image1b)

**Experimental results**

Both the static and dynamic parameters of the RED-Diodes from the Fig.1 and Tab.1 were measured. They are presented below in order to show how the changes in the doping profiles and carrier lifetimes between the platinum and palladium influence the leakage current, breakdown voltage, forward voltage drop and turn-off ruggedness.

**Static parameters**

From the viewpoint of an acceptably low leakage current, the useful range of annealing temperatures at the RED process starts from 600 °C (see Fig.2). In this range the magnitude of leakage current is close to that of the untreated device. This is because the acceptor levels of the platinum and palladium possess a relatively shallow position in the silicon bandgap (= E_c - 0.2 eV). For the RED-Diodes using the palladium, the increase of the leakage current due to the RED process was shown negligible up to the temperature of 140 °C in the 4.5 kV diodes with diameters of 51 and 91 mm [8]. It is worth emphasizing that the region modified by the RED was also placed directly into the space charge region of the anode junction which would not be possible in the case of proton or helium irradiation without...
the deterioration of leakage current. This means that the application of the RED process implies no restrictions in terms of the leakage current both for platinum and palladium.

![Graph showing leakage current at reverse voltage of 500 V (top) and 2000 V (bottom) after the RED of the Pd and Pt vs. the annealing temperature.](image)

Fig. 2: Leakage current at reverse voltage of 500 V (top) and 2000 V (bottom) after the RED of the Pd and Pt vs. the annealing temperature.

The major contribution of the RED process with the palladium is the creation of the lightly doped p-type layer at the anode junction (see Fig.1), because it increases the avalanche ruggedness in general. The lower p-type concentrations and the wider p-type regions bring a higher static breakdown voltage $V_{br}$ [6, 7]. The relative changes of the $V_{br}$ between the RED-Diode and the same diode without the RED process are compared in Fig.3. In the palladium RED-Diode, the lowest p-type concentration is obtained at 650 °C and higher. This explains the increase of the $V_{br}$ by 10 – 20 % between 500 and 650 °C. In the platinum RED-Diode, the relative changes of the $V_{br}$ are negligible, because there is no conversion from the n-type to p-type doping at the anode junction as shows the Fig.1.

In summary, the application of the RED process results in a higher $V_{br}$ of the palladium RED-Diode compared to that of the platinum. In principle, an increased $V_{br}$ is not the motivation for using the RED process. Nevertheless, it is a positive result that the magnitude of $V_{br}$ does not limit the application of RED process contrary to the proton irradiation, which reduces $V_{br}$ due to the activation of thermal donors when applied within the space charge region of a blocking junction [12].

![Graph showing relative change of the breakdown voltage after the RED of the Pd and Pt vs. the annealing temperature.](image)

Fig. 3: Relative change of the breakdown voltage after the RED of the Pd and Pt vs. the annealing temperature.

The forward voltage drop $V_f$ of the palladium RED-Diodes in Fig.4 monotonously decreases with increasing annealing temperature during the RED process. This can be explained by the fact that the annealing of the extended defects from helium implantation is higher at higher temperatures. Also the concentration of the shallower palladium deep levels increases at higher temperatures in comparison with the deeper ones. Altogether this supports the lowering of $V_f$.

![Graph showing forward voltage drop after the RED of the Pd and Pt vs. the annealing temperature.](image)

Fig. 4: Forward voltage drop after the RED of the Pd and Pt vs. the annealing temperature.
For the platinum RED-Diodes, the dependence of $V_f$ versus the annealing temperature is different. The $V_f$ is lower at lower temperatures because of much smaller amount of the electrically active platinum related deep levels incorporated in the silicon lattice. This situation changes above 700 °C, when the platinum incorporation in the substitutional sites increases significantly. The higher $V_f$ of the platinum diodes at 800 °C then reflects a higher solid solubility of the platinum compared to that of the palladium at the temperatures above 750 °C when the RED becomes irrelevant.

In summary, the $V_f$ of platinum RED-Diodes is lower than that of the palladium ones. However, this does not represent an advantage, because it is at the cost of a lower reduction of the carrier lifetime and recovery losses compared to the palladium RED–Diodes as is shown below.

**Dynamic parameters**

The reverse recovery of RED-Diodes was compared in the switching circuit with a very low stray inductance which is attributed by increasing $di/dt$ with time (see Fig.5). This is typical for the operation of a diode in the clamping circuit or in the free-wheeling position in the IGCT circuit without the $di/dt$ snubber (choke). In both these circuits, the demands on the ruggedness during turn-off are very high. The higher suppression of the DA the higher ON-state current can be safely turned-off. As there was no electron irradiation applied, the existence of the DA is pronounced already at a lower $di/dt$.

![Fig. 5a): Reverse recovery of the diodes subjected to the RED of Pd and Pt for the annealing temperature of 600 °C.](image)

![Fig. 5b): Reverse recovery of the diodes subjected to the RED of Pd and Pt for the annealing temperature of 700 °C.](image)

Fig. 5a) shows the reverse recovery for the annealing temperature of 600 °C at which the palladium RED-Diode gives the best performance. Fig.5b) shows the reverse recovery for the annealing temperature of 700 °C at which the platinum RED-Diode achieves the best performance. At both temperatures, we are not able to significantly reduce the maximal reverse recovery current $I_{RR}$ in the platinum RED-Diode. Consequently, the DA is very strong already at the line voltage of 1700 V and the device fails when this is increased to 1800 V. The palladium RED-Diode has the SOA up to 2400 V thanks to the stronger reduction of $I_{RR}$ and the existence of buried p-layer which suppresses the DA.

The results of the reverse recovery versus the forward voltage drop $V_f$ are summarized in Fig.6 for the whole range of annealing temperatures. The capability of the palladium RED-Diode increases with decreasing annealing temperature below 700 °C. The range of annealing temperatures from which one can choose a proper value to obtain the optimal device parameters is relatively wide. In the case of platinum, we are limited to the region 700 – 750 °C and the resulting parameters are still not competitive with palladium. Below 650 °C, the diodes fail already between 500 and 1000 V, because
of a high concentration of the extended defects from the helium implantation which are not converted to that of the platinum related deep levels.

Discussion

The RED-Diodes based on the low-temperature diffusion of platinum and palladium, which was enhanced by the radiation defects, have shown substantial differences in electrical parameters. Looking for a reason of this difference, we have measured the carrier lifetime using Open Circuit Voltage Decay (OCVD) method [13]. The dependence of lifetime on annealing temperature during the RED process corresponds to the distinct behaviour of electrical parameters shown above (see Fig.7).

Fig. 6: Technology curves of the diodes subjected to the RED of Pd and Pt for the dc link voltage of $V_r = 1700$ V during the reverse recovery. The tags show the annealing temperature during the RED process.

Fig. 7: OCVD lifetime of the diodes with and without the RED of the Pd and Pt versus the annealing temperature. The horizontal dashed line is that of the diode without lifetime control.
This dependence can be divided into two parts. Up to 650 °C, the lifetime of platinum diodes steeply increases with increasing temperature, because of increasing annealing rate of the extended defects from helium implantation. At 650 °C, the lifetime and device parameters of the platinum RED-Diodes become close to that of the untreated devices. Above 650 °C, the RED of platinum dominates and the lifetime decreases again. The best electrical parameters are achieved between 700 and 725 °C, where is the effect of the RED maximal. This is thanks to the domination of the Frank-Turnbull mechanism of diffusion [14] in agreement with the measurements of Jacob et al. made for the silicon with a high initial concentration of vacancies [15].

In the case of palladium, the annealing of extended defects from helium implantation is also higher at higher annealing temperature and the lifetime increases accordingly. Since the accumulation of palladium is much more intensive during the RED process under the presented experimental conditions, the steep increase of lifetime observed for the platinum is missing. A similar break in the lifetime vs. temperature dependence at 650 °C was observed, when the palladium was sputtered and sintered at 450 and 700 °C (see Fig. 4 in ref. [5] ), but the lifetime has never approached the value of untreated device as in the case of platinum. The lifetime of palladium RED-Diodes is much lower than that of the untreated diode (No RED) in the whole range of annealing temperatures up to 700 °C. The monotonous dependence of lifetime on the annealing temperature then results in the monotonous trade-off curve in Fig.6.

According to the doping profiles from Fig.1 and device parameters from Figs.5 and 6, the RED of palladium is more efficient at the temperatures between 500 and 650 °C. In this range, the RED of platinum was not found to work satisfactorily so far. It has been working neither for the RED from the sputtered platinum layers nor from the implanted ones with and without the additional annealing scheduled directly after the platinum implantation [16].

The remaining question is why is the RED of palladium so well visible already at about 500 °C, while that of the platinum only at 700 °C and with a much lower intensity, i.e. without the conversion of the n-type doping to that of p-type. A different solid solubility does not explain the observed difference, because that of the platinum is known to be higher. The big difference in the mass of the atoms and a different affinity to vacancies might be a reason for a different accumulation rate at the position of radiation defects. The similarities between the platinum and palladium, which lie in the quality of the electronic structure of the acceptor and donor deep levels resulting from the classical diffusion [9], are apparently conserved. However, the differences between the RED of platinum and palladium are rather of a quantitative nature. The accumulation of the platinum and platinum related defects by means of the extended defects from helium implantation is about one order lower compared to that of the palladium. Consequently, a significant lifetime reduction and the conversion from n-type to p-type doping are missing and the ruggedness of platinum devices is much lower.

**Conclusion**

The radiation enhanced diffusion of the platinum and palladium were compared in the light of the electrical parameters of fast recovery diodes rated at $V_{br} = 2500 \, \text{V}$ and $I_{FAV} = 150 \, \text{A}$. While the palladium provides excellent static device parameters and extends the reverse-bias safe operation area, the platinum is far from giving so good results. The reason for this difference was assigned to the possibility to enhance the accumulation of palladium and related defects at lower temperatures (500 - 650 °C), where the reduction of carrier lifetime is higher and the conversion from the n-type to p-type doping is still possible. In the case of platinum, the significant accumulation of the platinum and related defects is possible only in a narrow band of higher temperatures (700 - 725 °C), where the reduction of carrier lifetime is smaller and the conversion from the n-type to p-type doping is missing.

**References**