SOFT RECOVERY CHARACTERISTICS OF POWER DIODE BY PROTON IRRADIATION

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ABSTRACT – The soft reverse recovery characteristics of P-I-N power diodes by different lifetime killer were compared in this paper. It was concluded that the best local lifetime control at N^- base was achieved through the optimization of penetrated depth into the wafer by 5 MeV proton irradiation, resulting in significant soft recovery performance in our study. The results of 5~12 MeV electron irradiation and platinum diffusion were also discussed here.

1. INTRODUCTION

As is well known, the power diode has been widely used as the clamping diode or snubber diode in the application circuit of power GTOs and IGBTs. It is necessary to have the best soft recovery characteristics for mitigating the oscillation of re-applied voltage after turn-off of main switching device. The recovery characteristics of power diode strongly depend on the minority carrier lifetime at N-base. A reduction of this parameter is important for high frequency operation. The conventional lifetime control technique has been firstly achieved by high temperature(800~900 °C) diffusion of special deep-level impurities, such as gold or platinum[1], which makes recombination centers within the forbidden gap of silicon. Recently, the interests on the use of high energy electron irradiation(5~12 MeV), which has ease process and can cause vacancies or interstitial to be as recombination centers in silicon, to power semiconductors has been growing expanded[1,2]. However, by the electron irradiation, it is unable to have best optimization between on -state voltage drop and turn-off loss of power devices due to its fully penetration to silicon thickness. The research work concerning local lifetime control of proton irradiation instead of electron irradiation has increased in recent years[3,4,6,7]. In this work, the effects of different lifetime control techniques including platinum diffusion, electron and proton irradiation on the performance of power P-I-N diode were analyzed. In particular the soft recovery characteristics of 1000A/2000V power diode is described.

2. BASIC PRINCIPLES

In order to improve the soft recovery behavior of power diode, the various design concepts, such as lifetime killer technique, reducing p-emitter efficiency with lower doping, and additional shorted structures etc., can be applied. The suitable method among them is to introduce lifetime killer which can easily be applied in the mass production.

Fig.1 shows the typical reverse recovery wave-form of power P-I-N diode, in which the t_{rr} is the reverse recovering time and $S = t_b/t_a$ represents the softness factor. It is important to obtain high value of S for soft recovery characteristics of power diode used in the high-reliable power electronics application. Yet it is difficult to obtain soft recovery behavior from gold diffusion[4], the gold diffusion is excluded in this work. The platinum diffusion can have soft recovery behavior, because it has a best ratio of high injection-level carrier lifetime to low injection-level carrier lifetime τ_{HL}/τ_{LL}. This has been explained by early publications of B. J. Baliga[1].

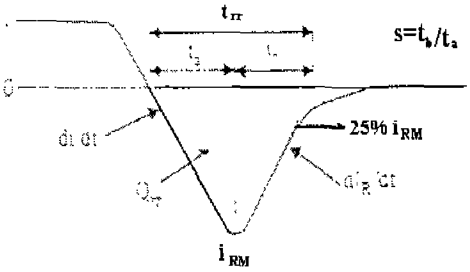

Fig.1 The typical reverse recovery waveform.

High energy electron irradiation can introduce some of bombardment defects, e.g. divacancies or pair of phosphorus-vacancy within the silicon lattice through the physical displacement of silicon atoms. These defects act as recombination centers for minority carriers and then provide a reduced carrier lifetime. If τ_0 is the pre-irradiation lifetime, Φ the irradiation dosage and K the damage coefficient which is closely related to process, then the post-irradiation lifetime τ is as follows:

$$1/\tau = 1/\tau_0 + K\Phi \text{ --------- } (1)$$

It is clear that a reduction of τ results from an increased Φ, and at same time t_{rr} (both of t_a and t_b reduces at same time) of diode is proportional to τ. Unfortunately high energy electron irradiation has large penetration depths and therefore creates an almost uniform carrier lifetime reduction throughout the whole thickness of silicon, resulting in uncontrollable softness of diode(e.g. uncontrollable t_a and t_b).

Recent results[5] of double-double deep level transient spectroscopy (DLTS) spectrum(DD-DLTS) demonstrated that the carbon-related centers of H(148 K), E(175 K), and H(205 K) are found to be the dominant recombination centers responsible for high-level lifetime τ_{HL} and low-level lifetime τ_{LL} after 2.73 MeV proton irradiation at 300°C for 8h vacuum annealing. It is mostly pronounced that the heavier proton atoms produced by proton irradiation are unable to fully penetrate the silicon wafer. The finite penetration depth introduces defects center primarily towards the end of their tracking position, therefore lifetime control is not uniform throughout the thickness of the silicon and the position of reduced lifetime region can be controlled by different energies of proton shown in Fig.2. Concerning for proton irradiated power diode, the reduced lifetime region must be located near the PN junction as shown in Fig.3. In this case the charge carrier densities are reduced around the junction compared with the device having uniform lifetime control technique, whereas the carrier densities located in the N-base are as same as that of uniform lifetime control.

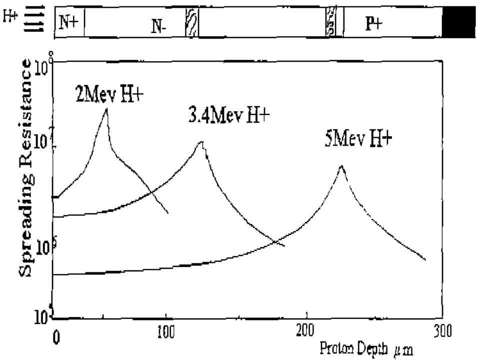

Fig.2 Proton depth vs. irradiated energy.

Consequently, during reverse recovering the peak reverse current has a lower value and slow decreases due to long carrier lifetime in the N-base region. The final results is that t_a is shorter and t_b is longer comparable to uniform lifetime control as for gold diffusion or electron irradiation.

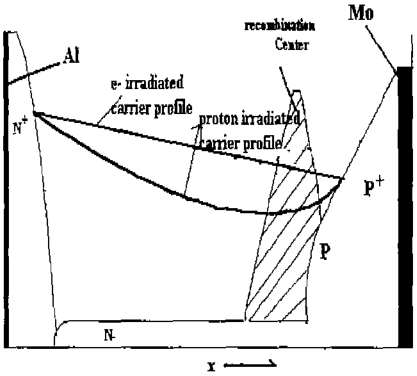

Fig.3 Carrier distribution in the power diode.

3. MAIN EXPERIMENT

(1) Device Fabrication

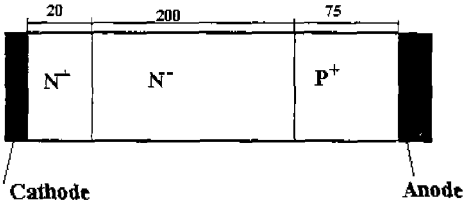

Fig.4 The P-I-N diode structure.

The power diode fabricated in this paper is conventional P-I-N structure as shown in Fig.4. The raw materials for 1000A/2000V high power diode are neutron transmutation doped(NTD) floating-zone silicon wafer with resistivity 60-75 Ω•cm and thickness 360-380 μm. The depth of Boron-Aluminum P-type diffusion junction is 75 μm. The N^- base width is 200μm. And phosphorus diffused N^+ emitter depth is 20μm. The main process is as follows:

1. (1) P-type diffusion by B-Al coating source at 1250°C/25h to form PNP layer.
2. (2) Lapping one-side P-type layer to have PN junction.
3. (3) Phosphorus diffusion to form N^+-layer on N-side of wafer.

For platinum diffused pellets platinum diffuse into wafer from anode-side in SiO_2 casein-glue coating source around 920-960°C for 40 minutes. And following process is alloy molybdenum discs for anode-terminal, aluminum for cathode and edge beveling etc.

In the case of local lifetime controlled device, the proton was irradiated by HI-13 tandem accelerator from the cathode-side of wafer after all process finished. The energy of 3~5 MeV was irradiated to control the depth of local lifetime area. For electron irradiated device 5~12 MeV electron was irradiated by liner accelerator in the post-all process from cathode of pellets. The steps of annealing process at 180°C/3h for electron irradiation and 250°C/12h for proton irradiation were carried out on each sample. The final pellet size is Φ50mm having average current of 1000 A.

(2) **Device Test**

For the static characteristics, the voltage blocking state for all three lifetime killer was all most same and there is no obviously difference of them for leakage current with rated 2000 V voltage at $T_j = 125$ °C, the maximum leakage current is below 20 mA. However deviation of the on-state voltage drop V_{TM} is somewhat large.

Minority carrier lifetime τ_p was determined from O.C.V.D.(open circuit voltage decay) measurements. In our case, τ_p equals to low-level carrier lifetime τ_{LL}. For platinum diffusion and electron irradiation, the τ_{LL} reduces from the original value of 30μs to 2μs. The on-state voltage drop V_{TM} was tested at the peak current of 3000A and switching time including t_{rr}, t_a and t_b were taken from measurement waveforms by reverse recovery method from LEM standard tester.

Our attention was mainly focused on the dynamic characteristics, i.e. the comparison of reverse recovery behavior vs different kinds of lifetime control technique. The test conditions for reverse recovery time t_{rr} is $I_T=1000$ A, $V_R = -100$ V, $di_A/dt = -100$ A/μs.

(3) **Experimental Results**

Table1 summarizes the results of platinum diffused diode. From this table, it is very clear that good softness recovery characteristics of power diode (i.e. large value of S = 0.9~1) can be obtained by platinum diffusion. High energy electron irradiation (see table 2) has hard recovery characteristics compared with platinum diffusion or proton irradiation. It is noted that electron irradiation also has the little higher voltage drop V_{TM} than that of proton irradiation, because the electron irradiation fully penetrate the wafer so that the minority carrier lifetime in the full N^- base keeps low. In table 2, the device *S–12 is firstly diffused by platinum at lower temperature 897°C of 40 minutes and then performed by 12 MeV electron irradiation. In this case the recovery performance is also harder (S=0.83). This fact indicates that the electron irradiation finally determines the hard recovery characteristics of power diode, because the ratio of high injection-level lifetime and low injection-level lifetime τ_{HL}/τ_{LL} is not optimized for 5~12 MeV electron irradiation.

In order to realize local lifetime control in vertically by proton irradiation, we select two different proton irradiation condition: 3.4 MeV with dosage of $\Phi = 2\times10^{11}/\text{cm}^2$ and 5 MeV of dosage $\Phi = 1.5\times10^{11}/\text{cm}^2$. The depth of 3.4 MeV, 5 MeV is around 120 μm and 220 μm respectively, as shown in Fig.2. It is predicted that the local lifetime area of the 3.4 MeV will be at the middle of N^- base and that of the 5 MeV will be near the area of P^+N junction. Table 3 summarizes the experimental results of different proton irradiation on dynamic characteristics of power diode.

From table 3, it is worthwhile to note that the low lifetime area of 3.4 MeV proton (the penetration depth is around 120 μm) is located far away the main junction of P^+N. Therefore the carrier recombination does not immediately happen when the reverse recovering procedure begins, resulting in very long t_a, and in the later stage(t_b) of reverse recovering the carrier recombination is much more fast since the low lifetime area is located in the middle of N-base. Therefore it results in the harder recovery process (S = 0.24~0.33) for 3.4 MeV proton irradiation. The depth of 5 MeV proton irradiation is around 220 μm, i.e. the low lifetime area is very close to the main junction, resulting in significant reduction of carrier lifetime τ_p at the local area near the P^+N junction. In this case the carrier lifetime at the N^- base still keeps much longer, resulting in large value of t_b and good softness recovering behavior S = 0.96~1. At the same time the pronounced features of 5 MeV proton irradiation diode is its low on-state voltage V_{TM} compared with that of electron irradiated diode.

4. CONCLUSION

From our earlier experiments on the P-I-N structure of high voltage power diode, it is very difficult to obtain good softness recovery characteristics by gold diffusion or electron irradiation.

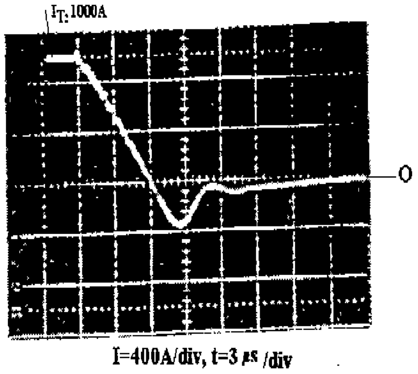

Fig.5 The test waveform of diode.

However from this work on power P-I-N diode by 3.4~5 MeV proton irradiation, the good soft recovery characteristics is achieved. Fig.5 shows its typical recovery waveform. The fabrication process of power diode and test was made in Xi'an Power electronics Research Institute, China. High energy electron, proton irradiation were performed at China Institute of atomic Energy Science.

5. REFERENCES

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Table 1. Power diode performance by Platinum diffusion

Sample	Pt Temp.	V_{TM}(V)	t_{rr}(μs)	t_a(μs)	t_b(μs)	**S= t_b/t_a**	V_{RRM}(V)
S-15	920°C	1.80	5.0	2.5	2.5	**1.0**	2000
S- 5	940°C	2.09	3.8	2.0	1.8	**0.9**	2000
S-10	960°C	2.21	3.4	1.8	1.7	**0.94**	2000

Table 2. Power diode performance by electron irradiation

Sample	e^-energy	dosage(cm^{-2})	V_{TM}(V)	t_{rr}(μs)	t_a(μs)	t_b(μs)	**S=t_b/t_a**	V_{RRM}(V)
6-46	5.0MeV	$\Phi\ 5\times10^{13}$	1.98	5.2	2.8	2.4	**0.85**	2000
6-37	5.0MeV	$\Phi 5\times10^{13}$	1.83	5.4	3.0	2.4	**0.80**	2000
6-42	12MeV	$\Phi\ 3\times10^{13}$	1.77	6.0	3.6	2.4	**0.66**	2000
6-43	12MeV	$\Phi 3\times10^{13}$	1.75	6.0	3.2	2.8	**0.87**	2000
6-20	12MeV	$\Phi 3\times10^{13}$	1.80	5.6	3.2	2.4	**0.75**	2000
*S-12	Pt897°C+ e^- 12MeV	Pt: 40minutes $e^-\ \Phi\ 9\times10^{12}$	2.21	5.5	3.0	2.5	**0.83**	2000

Table 3. Power diode performance by proton irradiation

Sample	H^+ energy	dosage (cm^{-2})	V_{TM} (V)	t_{rr} (μs)	t_a(μs)	t_b(μs)	**S=t_b/t_a**	V_{RRM}(V)
06-2	3.4MeV	$\Phi 2.0\times10^{11}$	1.80	8.0	6.0	2.0	**0.33**	2000
06-49	3.4MeV	$\Phi 2.0\times10^{11}$	1.75	9.3	7.5	1.8	**0.24**	2000
06-30	5.0MeV	$\Phi 1.5\times10^{11}$	1.56	5.0	2.6	2.5	**0.96**	2000
06-23	5.0MeV	$\Phi 1.5\times10^{11}$	1.60	6.0	3.0	3.0	**1.00**	2000
* S- 13	Pt 897°C + H^+ 5MeV	Pt:40min diff. H^+: $\Phi 1.5\times10^{11}$	1.63	5.0	2.5	2.5	**1.00**	2000