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Reverse recovery characteristics and defect distribution in an electron-irradiated silicon p–n junction diode

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Abstract

Electron irradiation was performed to enhance the switching speed and thereby to reduce the energy loss of a p–n junction diode. The reverse recovery time decreased significantly but other electrical deterioration such as leakage current and on-stage voltage drop due to the electron irradiation was found not to be much. Also the defect distribution and the type of the electron irradiation-induced defects are discussed based on the deep level transient spectroscopy (DLTS) analysis results and the secondary ion mass spectrometry (SIMS) depth profiles of the silicon substrate.

Keywords: Electron irradiation; Energy loss; Power device; Switching speed; Defects; Minority carrier lifetime

1. Introduction

In silicon power devices operating at higher frequencies long minority lifetime causes many problems such as switching delay and excessive power loss during switching. Therefore, it is strongly needed to control the minority carrier lifetime to match the frequency level of the power device [1]. In power device fabrication technology, the minority carrier lifetime is reduced by introducing efficient recombination centers either by the diffusion of metallic impurities such as gold and platinum immediately before metallization, or by high energy irradiation, which is usually the last step in the processing sequence. The gold or platinum diffusion technique was commonly used previously, but the electron or proton irradiation technique is preferred these days.

The advantages of using these techniques to control the lifetime in power devices are as follows [1]: (a) the irradiation can be performed at room temperature after complete device fabrication and initial testing of the characteristics; (b) the lifetime is controlled by the radiation dose which can be accurately metered by monitoring the electron current during irradiation; (c) a much tighter distribution in the device characteristics can be achieved because of the improved control over the recombination center density; (d) the irradiation process allows trimming the device characteristics to the desired value by using several irradiation steps because the radiation is performed after complete device fabrication, thus allowing device testing between consecutive irradiation; (e) the irradiation damage can be annealed out by heating the devices above 400 °C, thus allowing the recovery of devices that may have had an overdose during irradiation and (f) the irradiation process is a cleaner and simpler process as compared with impurity diffusion and avoids any possible contamination between the processing of devices requiring high lifetime and those requiring low lifetime. These advantages have made the electron irradiation process very attractive for manufacturing power device.

There have been many reports on the nature and distribution of the defects in silicon induced by the electron or proton irradiation [2–6]. However, the electrical performance of electron-irradiated-power devices particularly during the turn-off transient have not been thoroughly understood yet [7,8]. Particularly, the negative effects of the electron irradiation on the electrical properties of p–n junction diodes other than switching speed enhancement have not nearly been reported.

In this paper the effects of electron irradiation on the electrical properties of a p–n junction diode are reported. The electrical properties include leakage current and forward voltage drop as well as switching speed. The p–n junction is a basic device structure found in most power devices such as fast recovery diodes, thyristors and IGBTs. The nature

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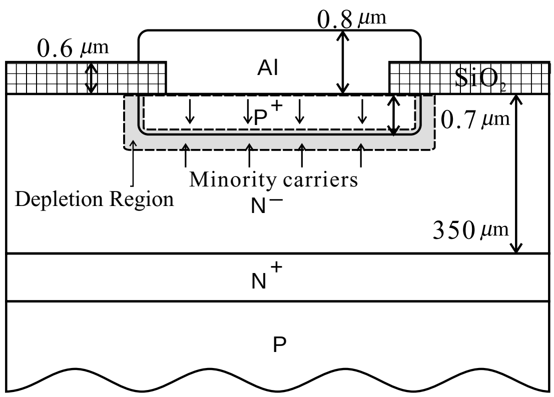

Fig. 1. Schematic diagram of a p–n junction diode structure.

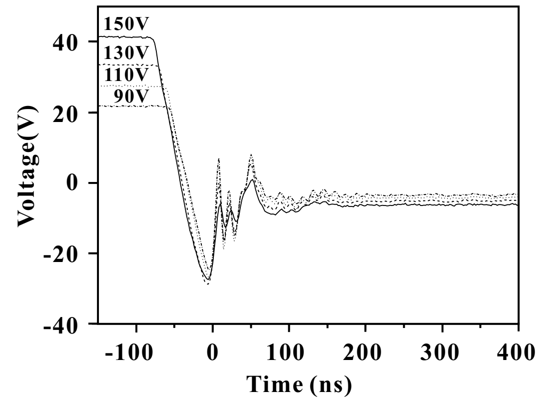

Fig. 2. Voltages measured at various forward injections for the p–n junction diode.

and distribution of the defects induced in the p–n junction diode by electron irradiation are also discussed.

2. Experimental

The p–n junction diodes were made by ion implantation on 4 in. p-type (1 1 1) Si wafers with the resistivity of 20 Ω cm. n^+ layers were formed by doping arsenic. Next n^--epitaxial layers were grown on the n^+ layers by the vapor phase epitaxy technique. The junction depth of n^--epitaxial layers are about 350 μm. p–n junctions were made by boron ion implantation on the n^--epitaxial layers. The boron implantation dose is 10^{14}/cm^2 and the p–n junction depth is 0.7 μm. The samples were irradiated by electrons with the energy of 12 MeV and various doses. They were then annealed at 1000 °C for 1 h in nitrogen atmosphere. The transient characteristics were measured by a digital oscilloscope, while forward and reverse voltages were alternately applied to the diode. The structure of the p–n diode used for the transient measurements is shown in Fig. 1. The circuit to measure the transient current used in this study is the same as that in [6] and well described therein. The deep level transient spectroscopy (DLTS) analysis, the current–voltage (*I*–*V*) profiling under forward and reverse biases and the capacitance–voltage (*C*–*V*) profiling were performed for the electron-irradiated and unirradiated diodes to measure the defect distribution, the voltage drop, the leakage current, and the defect nature, respectively.

3. Results and discussion

Fig. 2 shows turn-off transients of electron ($E = 12$ MeV, $Q = 800$ kgy)-irradiated p–n junction diodes. The reverse recovery times t_{rr} and reverse recovery charges Q_{rr} of the diode under four different forward biases 90, 110, 130 and 150 V are compared and it appears that t_{rr} and Q_{rr} increase as the forward bias increases. Larger values of t_{rr} and Q_{rr} mean a lower switching speed and bigger energy loss. As shown in Fig. 3 t_{rr} and Q_{rr} decrease significantly with increasing the electron irradiation dose. The reverse recovery time t_{rr} for the irradiated diode with the electron dose of 5 Mrad is one-third of that for the unirradiated one. On the other hand, t_{rr} and Q_{rr} also increase with increasing the forward bias but the degree of change in t_{rr} and Q_{rr} is not as much as that with the increase of the irradiation dose. Electron irradiation is mostly performed in the depletion region of the p–n junction to form crystallographic defects such as Si vacancy and Si interstitials. Under the forward bias most minority carriers draw back from the p–n junction and excess minority carriers are injected from the oppositely doped region. The amount of the reverse recovery charge, Q_{rr} is the product of the minority carrier lifetime and the forward current. At turn-off some of the excess minority carriers are removed by recombination and others come out as a reverse current. Therefore, the integration of the reverse current will increase with increasing forward current or forward bias. Under the reverse bias the minority carriers are injected into the depletion region from outside. Also as shown in Fig. 1, holes are injected into the depletion region of the n^--Si while electrons into that of the p^+-Si. These minority carriers injected into the depletion region drift with high energies under strong reverse bias. Their life is over when they are captured by the defects in the depletion region.

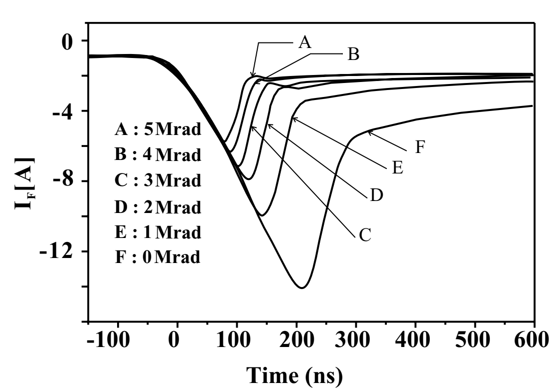

Fig. 3. The recovery current waveforms of the p–n junction diode irradiated by 12 MeV electrons with different doses.

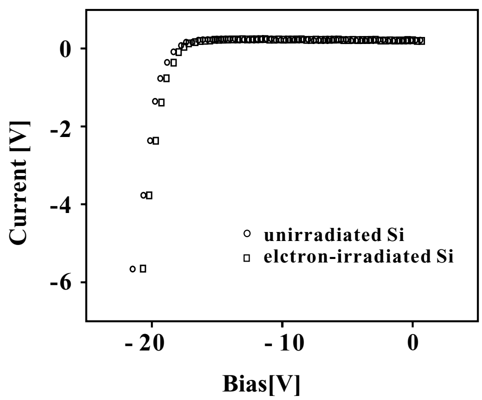

Fig. 4. Current–voltage (*I*–*V*) characteristics of the electron-irradiated and unirradiated p–n junction diodes under the reverse bias.

Power semiconductor devices repeat on and off corresponding to their frequencies, say, from the forward bias to the reverse bias and again to forward bias over and over again. Power loss occurs at every turn-off. The power loss is reduced accordingly if the minority carrier lifetime is shortened by electron irradiation since t_{rr} and Q_{rr} are reduced.

If electron irradiation is conducted onto power devices the switching speed will increase but other electrical properties such as leakage current and forward voltage drop will be probably deteriorated. The *I*–*V* characteristic curves under the reverse bias are shown both for electron-irradiated and unirradiated p–n junction diodes in Fig. 4. Little difference is found between the two cases, which proves the fact that the defects formed by electron irradiation do not cause serious junction leakages as are anticipated.

On the other hand, the difference in forward voltage drop by electron irradiation is shown in Fig. 5. We can see there is some but not much change in forward voltage drop due to the irradiation. The minority carrier lifetime decreases by electron irradiation and, in turn, the electrical resistivity increases, which results in the IR drop under forward bias.

Fig. 6(a) and (b) show the distribution of defects and n-type doping concentration in the silicon substrate induced by electron irradiation, respectively. The depth profiles of defects and n-type doping were obtained using the DLTS and the automatic spreading resistance(ASR) techniques, respectively. The defect density is about 10^{12} cm^{-3} in the depth less than 4.2 μm and about 10^{13} cm^{-3} in the depth more than 4.2 μm. On the other hand, the doping concentration is about 4.5×10^{14} cm^{-3} in the depth range less than 7 μm. If we look at the n-type doping profile in Fig. 6(b) carefully, we can see that the doping level is slightly higher in the depth range of 4.5–7 μm than in the depth below 4.5 μm (Fig. 6(b)). This higher doping level may be attributed to the electron-irradiated defects because the defect density is also higher above 4.5 μm rather than below 4.5 μm (Fig. 6(a)). Considering that the electron-irradiated defects have an effect elevating the n-type doping level, we may conclude that the type of the electron-irradiated defects is donor-like rather than acceptor-like.

The DLTS analysis results are also given as a graph of concentration ($-\Delta C/C$) versus temperature in Fig. 7. Two main peaks appear near 150 and 240 K in this graph although the peak positions are slightly different depending upon the signal sampling time (t_1, t_2 and t_3). The existence of two main peaks implies that there exist two kinds of defects with different energy levels. We can obtain the trap concentration from Fig. 7 as follows [9].

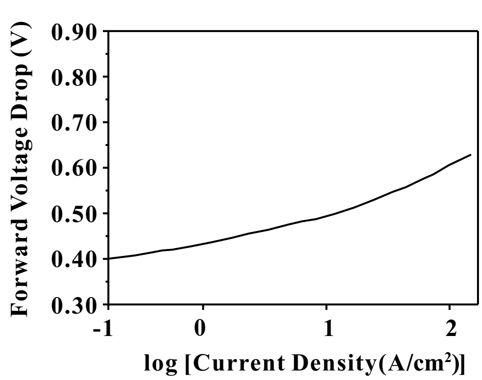

Fig. 5. Difference in forward voltage drop of the p–n junction diode as a function of the current density due to electron irradiation and subsequent annealing.

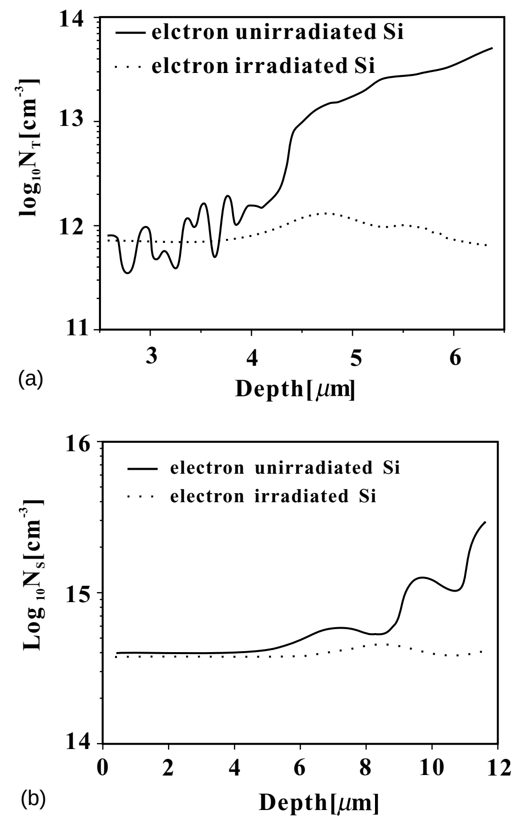

Fig. 6. (a) Deep level concentration and (b) the n-type doping concentration profiles of the silicon substrates irradiated and unirradiated by 12 MeV electrons with a dose of 800 kgy as measured by DLTS.

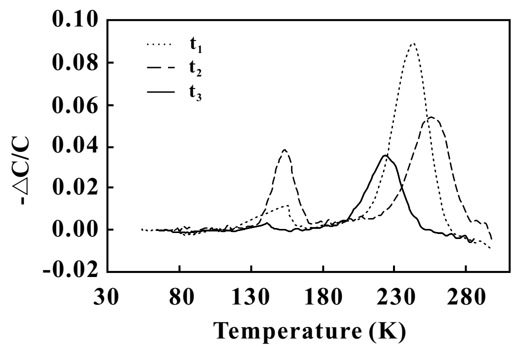

Fig. 7. The DLTS spectra of the silicon substrate irradiated by 12 MeV electron with a dose of 800 kgy.

If the trap density is much less than the background carrier concentration (this is true in our case since the trap density is about one order lower than the background carrier concentration), the amplitude of the exponential decay, ΔC, can be related to the trap concentration N_T by the expression

$$N_T \cong \frac{2(N_D - N_A)\Delta C}{C} \qquad (1)$$

where $N_D - N_A$ is the background carrier concentration in the bulk material and C the steady-state capacitance of the diode. The sign, or polarity, of the transient is indicative of the type of trap present. A negative amplitude transient ($\Delta C/C < 0$) indicates that this is a majority carrier trap. The capacitance transient due to minority carrier traps has a positive amplitude ($\Delta C/C > 0$). Fig. 7 tells us that $\Delta C/C > 0$ in our case indicating that the type of the traps are minority carrier traps.

We can also obtain the trap activation energy from Fig. 8 which is the Arrhenius plot made by DLTS analysis. The details of the procedure obtaining the trap activation energy is as follows.

The rate of thermal emission of carriers from a deep state at temperature T can be expressed as

$$\rho_n = \sigma_n V_{th} N_C \exp\left(-\frac{\Delta E}{kT}\right) \qquad (2)$$

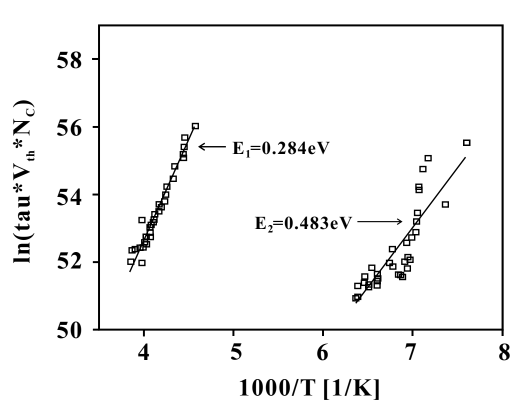

Fig. 8. The Arrhenius plots for the DLTS analysis results shown in Fig. 7.

where σ_n is the capture cross-section, V_{th} the thermal velocity, N_C the background carrier concentration and $\Delta E = E_C - E_T$ for electron traps and $\Delta E = E_T - E_V$ for hole traps. Since ρ_n is equal to the time constant τ, Eq. (2) can be written as

$$\tau V_{th} N_C = \sigma_n^{-1} \exp\left(-\frac{\Delta E}{kT}\right) \qquad (3)$$

Thus

$$\ln(\tau V_{th} N_C) = \left(\frac{\Delta E}{k}\right)\left(\frac{1}{T}\right) - \ln \sigma_n \qquad (4)$$

Hence the slope of the straight line in Fig. 8 gives the trap activation energy and whose intercept at $T = \infty$ gives the capture cross-section. In our case we can see in Fig. 8 that the energy levels of the two kinds of traps are 0.284 and 0.483 eV below the conduction band edge E_C (equivalent to 0.836 and 0.637 eV above the valence band edge E_V since the energy band gap for silicon at room temperature is 1.12 eV). According to Evwaraye and Baliga's report [10] there are three deep levels at 0.27, 0.71 and 0.87 eV above the valence band in the case of electron irradiation and the deep level at 0.71 eV above the valence band is dominant among these three deep levels, i.e., controls the minority carrier lifetime in n-type silicon. They also reported that the deep level at 0.71 eV is induced by divacancy. In comparison with Evwaraye's report, the deep levels 0.284 and 0.483 eV below the conduction band seem to correspond to those 0.87 and 0.71 eV above the valence band, respectively. Some discrepancy may be attributed to difference in the accuracy of the DLTS analysis system.

4. Conclusions

From the above discussion we can see that the switching speed can be effectively increased and thus the energy loss of the p–n junction diode can be reduced by electron irradiation. On the other hand, it appears that the junction leakages and the forward voltage drop which are anticipated to increase are negligible. Also the analysis results of DLTS and *C–V* profiling indicate that the defects in the p–n junction diode induced by electron irradiation are donor-like ones the energy levels of which are 0.284 and 0.483 eV. Considering all the experimental results in this study it may be concluded that electron irradiation is a very useful technique in improving the switching characteristics of the p–n junction diode power device.

Acknowledgements

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