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Effect of Ionizing Radiation on the Silicon IMPATT Diode Characteristics

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Abstract

We investigated the effect of ^{60}Co γ-irradiation (doses from 10^2 to 2×10^6 Gy), both without and with heat annealing, on silicon IMPATT diode parameters. It is shown that such treatments improve the diode characteristics (particularly decrease the reverse current and increase both the output and the diffusion length of the minority charge carriers) due to radiation-enhanced processes.

1. Introduction

At present a number of technological procedures are known that enable to purposefully change the parameters of device structures based on different semiconductor materials [1-4]. Various methods of gattering and structural - impurity ordering have been developed that can improve the device structure parameters [2, 3]. During manufacturing devices often accumulate various structural defects generated in them during chip formation, dissipative welding and/or thermocompression bonding. This results in both degradation of parameters in the finished product and yield reduction. For such devices the restoration of their properties poses a problem. Conventional heat treatment would not do in this case because the annealing temperature is limited (as the contacts must not be fused). To apply other treatments, one has to know with certainty the nature of the defect as well as the treatment peculiarities, themselves neither of which is often taken into account in practice.

We did manage to improve the parameters of silicon impact-avalanche and transit-time (IMPATT) diodes by γ-irradiation of finished production (packaged diodes) or generator units (IMPATT diodes in a cavity), both with and without heat annealing. Such treatments do not generate structural defects, nor do they result in material compensation and widening of the space charge region (SCR) [1, 5].

2. Experimental Procedure

The diodes studied were fabricated using boron diffusion from vapor phase into the $n - n^+$ Si substrate (the charge carrier concentration in the n layer was $(3 + 5) \times 10^{16}$ cm^{-3}). The reverse mesa diameter was 5×10^{-3} cm, and the avalanche-breakdown voltage V_B was 19-20 V. The starting microwave output P^*_{out} did not exceed 35 mW at operating current $I_{op} = 100$ mA. The reverse branches of $I - V$ curves were taken and the diffusion length of minority charge carriers L_p and output P_{out} were measured both before and after the corresponding treatments. To treat the diodes studied we used ^{60}Co γ-radiation (doses from 10^2 to 2×10^6 Gy, dose rate 3 Gy/s), both with and without heat annealing, at temperature T = 200-250°C for 40-60 min.

3. Experimental Results and Discussion

Shown in Figure are the dose dependencies of the reverse current I_R (at the reverse bias $V_R = 0.9$ V), diffusion length L_p and the relative change of the mean microwave output, P_{out}/P^*_{out}. One can see that both I_R and L_p dose dependencies correlate with change of P_{out}/P^*_{out} change due to ^{60}Co γ-irradiation. According to [6],

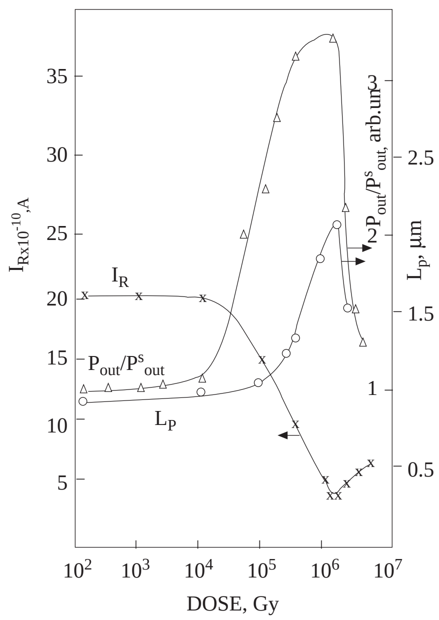

Figure 1. Dependencies of the silicon IMPATT diode parameters on the absorbed dose of ^{60}Co γ-irradiation: 1- Reverse current I_R; 2- Diffusion length of the minority charge carriers L_p; 3- Output P_{out}.

$$P_{out} = (\Delta T w / \epsilon V_B R_T S^{1/2})^2 \mu_{eff} \rho_B, \quad (1)$$

where ΔT is the difference between the temperatures of the SCR and the ambient, w is the SCR width, ϵ is permitivity of the diode material, R_T is the diode heat resistance, S is the $p-n$ junction area, μ_{eff} is the effective mobility of charge carriers and ρ_B is the diode resistivity.

From Expression (1) it is evident that if w, V_B and ρ_B remain constant, then the P_{out} increase due to ^{60}Co γ-irradiation may result from changes in R_T, S and/or μ_{eff}. Indeed, the direct heat resistance measurements for the IMPATT diodes studied have shown that R_T was decreasing during γ-irradiation. This results from the increase of the effective cross section area of the active region where heat dissipation occurred. In addition, the effective mobility μ_{eff} may grow as a result of the radiation-enhanced gettering due to a decrease in the number of scattering centers. The last statement is circumstantially evidenced by the results of direct electron-probe measurements of the diffusion length L_p both before and after γ-irradiation of test structures fabricated from the same wafers that were used to fabricate the IMPATT diodes studied (see Figure, curve 2).

We have studied also the effect of the low-temperature (T = 200-280°C) annealing on the output P_{out} and the reverse current I_R for the IMPATT diodes preirradiated by the ^{60}Co γ-quanta. The corresponding results are given in Tables 1-3.

Table 1. Effect of ^{60}Co γ-irradiation (without and with heat annealing at 200°C for 1 hour) on the P_{out}/P^{*}_{out} and I_R/I_R^S ratios for silicon IMPATT diodes.

Irradiation dose	Without heat annealing		With heat annealing	
Gy	P_{out}/P_{out}^S	I_R/I_R^S	P_{out}/P_{out}^S	I_R/I_R^S
1×10^2	1.00	1.00	1.00	1.00
5×10^2	1.00	1.00	1.06	1.00
1×10^3	1.05	1.00	1.10	1.00
1×10^4	1.66	1.00	1.82	0.50
1×10^5	2.61	0.75	3.01	0.32
5×10^5	2.93	0.50	3.93	0.28
7×10^5	3.12	0.35	4.12	0.20
1×10^6	1.54	0.25	3.07	0.32
2×10^6	1.54	0.20	1.00	0.70

Table 2. Effect of the temperature of heat annealing (for 1 hour) on the P_{out}/P_{out}^S and I_R/I_R^S ratios for ^{60}Co γ-irradiated (dose of 5×10^5 Gy) silicon IMPATT diodes.

Diode No:	Temperature of heat annealing, °C	Before heat annealing	annealing	After heat	
		P_{out}/P_{out}^S	I_R/I_R^S	P_{out}/P_{out}^S	I_R/I_R^S
1	100	2.90	0.50	2.90	0.45
2	140	2.90	0.37	3.13	0.15
3	180	2.90	0.37	3.50	0.14
4	200	2.90	0.28	3.91	0.12
5	250	2.90	0.35	3.74	0.10
6	280	2.90	0.37	3.02	0.12

Table 3. Effect of the duration of heat annealing (at 200°C) on the P_{out}/P_{out}^S and I_R/I_R^S ratios for ^{60}Co γ-irradiated silicon IMPATT diodes (dose of 7×10^5 Gy).

Diode No:	Duration of heat annealing, min	Before heat annealing P_{out}/P_{out}^S	Before heat annealing I_R/I_R^S	After heat P_{out}/P_{out}^S	After heat I_R/I_R^S
1	20	3.02	0.50	3.02	0.50
2	40	3.02	0.40	3.76	0.19
3	60	3.02	0.40	4.09	0.12
4	80	3.02	0.45	3.81	0.16
5	100	3.02	0.35	3.59	0.17
6	120	3.02	0.35	3.43	0.20

One can see that the low-temperature annealing after ^{60}Co γ-irradiation increases P_{out} as well. It should be noted that the above heat treatment of the non-irradiated IMPATT diodes either resulted in a decrease of the output P_{out}, or, at best, did not change it.

4. Conclusion

Thus it may be concluded that ^{60}Co γ-irradiation (doses up to 10^6 Gy) of silicon IMPATT diodes may lead to the improvement of their respective parameters. In particular, the output is increased due to the radiation-enhanced processes in the device active area. Introduction of such a technological procedure into manufacturing of such devices will result in a yield rise.

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