Influence of electron irradiation on the switching speed in insulated gate bipolar transistors

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Abstract: The influence of electron irradiation on the switching speed in insulated gate bipolar transistors (IGBT) with different epitaxial layer thicknesses is discussed in detail. The experimental results prove that the fall time of IGBT increases when increasing the thickness of the epitaxial layer. However, there is no obvious difference between the ratios of the fall time after irradiation to those before irradiation for different epitaxial layer thicknesses. The increase in switching speed of the IGBT is accompanied by an increase in the forward drop, and a trade-off curve between forward voltage drop and fall time of IGBT is presented.

Key words: electron irradiation; fall time; switching speed; IGBT
DOI: 10.1088/1674-4926/30/6/064008 **EEACC:** 2560P

1. Introduction

The insulated gate bipolar transistor (IGBT) is a new power semiconductor device that offers the advantages of high operating forward conduction current density and high input impedance of the MOS gate structure and has become the main switching device in power electronic applications in recent years[1−5]. There are many application ranges for IGBTs, such as line operated phase control circuits, motor drives, and UPS. Different applications need different switching speeds. Electron irradiation is one of those processes used by some manufacturers to make IGBTs with various speeds for particular ranges of operating frequencies[6].

Electron irradiation introduces recombination centers in the n-base region leading to a reduction of the minority-carrier lifetime and an increase of the switching speed of the IGBT[7]. Compared with other approaches, for example, gold or platinum diffusion and neutron irradiation, the electron irradiation offers the advantages of being a clean process that can be carried out at room temperature after complete device fabrication and pre-irradiation testing[8, 9]. This process also offers better control of the lifetime with a tighter distribution of the device characteristics. This paper provides a detailed discussion about the influence of the electron irradiation at different doses on the switching speed in insulated gate bipolar transistors with different epitaxial layer thicknesses.

2. Experimental procedure

The IGBT devices used for this study are of the punch-through type and were fabricated by using an n-channel polysilicon-gate DMOS process using n-type epitaxial layers grown on p^+ substrates to obtain a 600-V forward reverse-blocking capability. There are three different epitaxial layer thicknesses: 52 μm (1# wafer), 49 μm (2# wafer), and 46 μm (3# wafer). The resistivity of the epitaxial layer is 24 Ω·cm in each wafer. A higher resistivity will increase the forward and the reverse-blocking capability, and it also increases the forward voltage drop. Five devices in every wafer were chosen in this study. Before irradiation, the static state and the switching characteristics of these devices were measured by a Tesec 3620-TT and a Tesec 3430-SW, respectively. These devices were found to conduct 20 A of forward current at a forward voltage drop of 2.35 V. The gate turn-off tests on these devices were performed at a collector current of 20 A with a blocking voltage of 300 V. The fall time t_f is defined as the time it takes for the collector current to decrease from 90% of its steady-state value to 10%. The fall times of these devices are shown in Fig. 1. It can be seen that the difference between the fall times of devices made from the same wafer is much smaller than those of devices made from different wafers. The fall time increases when increasing the epitaxial layer thickness,which is consistent with the basic theory.

The electron irradiation was performed at an energy of 12 MeV with doses of up to 8 Mrad to reduce the lifetime. The fifteen devices were divided into five groups, and the three devices in one group come from different wafers.The five groups

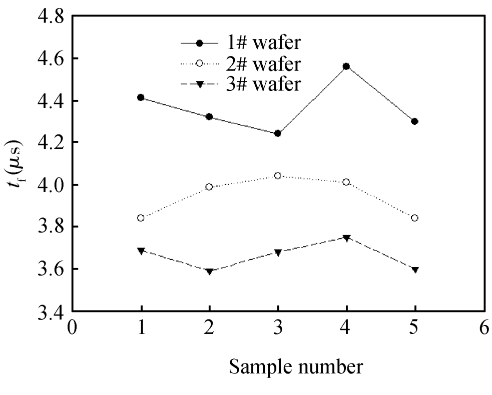

Fig. 1. Fall time of IGBT in different wafers before irradiation.

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Received 8 January 2009, revised manuscript received 11 February 2009

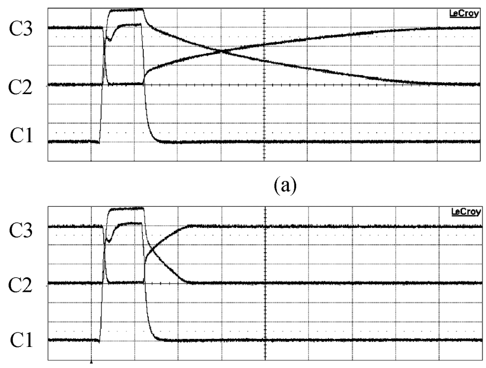

Fig. 2. Switching waveform of an IGBT (a) before and (b) after irradiation with a dose of 8 Mrad.

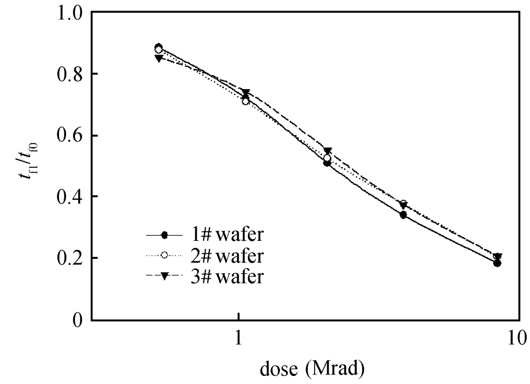

Fig. 3. Ratio of the fall time after irradiation to that before irradiation.

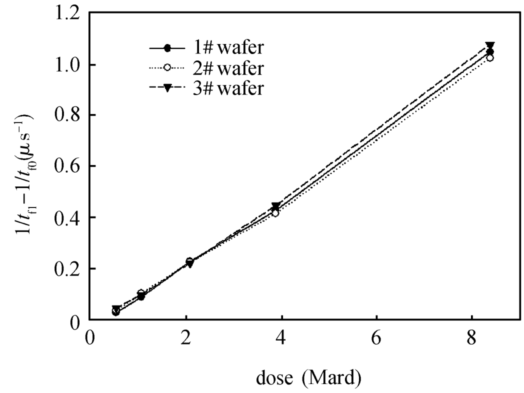

Fig. 4. Curves of $1 / t_{f1} - 1 / t_{f0}$ versus dose in different wafers.

have different irradiation doses of 0.5, 1, 2, 4, and 8 Mrad. All the irradiations were performed with the electron beam impinging on the emitter surface of the devices packaged in the TO-3P type. After irradiation, the devices were annealed at 250 °C for 1.5 h. The device characteristics were then measured by the Tesec 3620-TT and the Tesec 3430-SW to evaluate the effects of the electron irradiation. It should be noted that, although previous papers reported that their annealing temperature was 140 °C in this study annealing at 140 °C does not work at all.

3. Device characteristics

Electron irradiation has a significant effect on the switching speed enhancement in an IGBT. Figure 2 shows the switching waveform of an IGBT before and after irradiation with a dose of 8 Mrad. The horizontal axis is time, and the time base is 1 μs/div. Channel 1 is the gate voltage, channel 2 is the collector current, and channel 3 is the collector voltage. The electron irradiation reduces the fall time from 4.51 to 0.786 μs.

The results of the fall time measurements after irradiation are shown in Fig. 3. Because the fall time varies among different devices, we use the ratio of the fall time after irradiation to that before irradiation to describe the impact of irradiation on the switching speed. It can be seen that the fall time decreases with increasing irradiation dose, despite of the epitaxial layer thickness. Though the fall time increases when increasing the epitaxial layer thickness, there is no obvious difference between the ratios of the fall time after irradiation to those before irradiation for different epitaxial layer thicknesses. Since the fall time is dominated by the recombination tail, it can be anticipated that the fall time (t_f) should decrease proportional to the minority-carrier lifetime (τ). Their relationship can be written as

$$t_f = n\tau, \tag{1}$$

where n is the proportional coefficient. It has previously been shown that the minority-carrier lifetime after irradiation (τ_f) depends on the pre-irradiation lifetime (τ_i) and the electron irradiation dose (Φ), which is given as follows[10]:

$$\frac{1}{\tau_f} = \frac{1}{\tau_i} + K\Phi, \tag{2}$$

where K is the irradiation damage coefficient; it can be rewritten with the fall time after irradiation (t_{f1}) and the fall time before irradiation (t_{f0}) as

$$\frac{1}{t_{f1}} = \frac{1}{t_{f0}} + \frac{K}{n}\Phi = \frac{1}{t_{f0}} + K'\Phi. \tag{3}$$

Equation (3) can be rewritten as

$$\frac{1}{t_{f1}} - \frac{1}{t_{f0}} = K'\Phi. \tag{4}$$

Figure 4 shows the curves of $\frac{1}{t_{f1}} - \frac{1}{t_{f0}}$ versus the dose in different wafers. The three curves coincide. This means that the slopes of the three curves, K', are the same. Since the proportional coefficients, n, are the same in different wafers, the irradiation damage coefficients, K, are also the same in different wafers. This is because the electron irradiation controls the minority-carrier lifetime by the introduction of recombination centers in the n-base region. The concentration of recombination centers depends on the material, the irradiation dose, the energy, the annealing temperature, and time. Since the other parameters are the same for the three wafers, the concentration of recombination centers is only proportional to the irradiation dose. Since the epitaxial layer thicknesses of the three wafers are nearly the same, the numbers of recombination centers are the same in different wafers when the irradiation dose is the same. So, the irradiation damage coefficients, K, are also the same in different wafers.

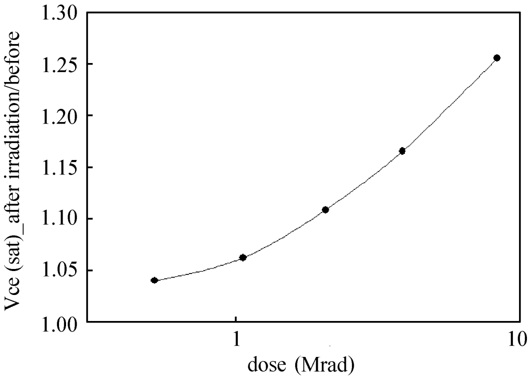

Fig. 5. Increase in the forward voltage drop with increasing radiation dose.

As in the case of other bipolar devices, a decrease in the minority-carrier diffusion length causes a decrease in the forward conduction current density, which means an increase in the forward voltage drop for the fixed current. The increase in the forward voltage drop with increasing radiation dose is shown in Fig. 5. In this figure, the forward drops were measured at a collector current of 20 A. The forward drop increases from 2.35 V before radiation to about 3 V after radiation at a dose of 8 Mrad. That means that the forward drop increases by 27.6% after radiation at a dose of 8 Mrad. Thus, the increasing in switching speed of the IGBT is accompanied by a loss in the current handling capability; however, the forward conduction characteristics of an IGBT remain far superior to those of the power MOSFET. Since a short fall time is desirable to reduce switching losses and a low forward voltage drop is desirable to reduce the conduction losses, it becomes necessary to make a trade-off between these device characteristics. This can be most effectively done by using a plot of the ratio of the forward voltage drop before and after irradiation versus the ratio of the fall time before and after irradiation, as shown in Fig. 6. It can be seen that the IGBT devices exhibit the unique feature of being able to continuously adjust the switching speed and the forward drop without affecting other device parameters. Depending upon the application, the appropriate device characteristics can be selected by choosing the irradiation dose. Thus, the IGBT can be tailored to match the power switching requirements of a broad range of applications.

4. Conclusion

The experiment results prove that the fall time of IGBTs increases when increasing the epitaxial layer thickness.Electron irradiation can be effectively utilized to control the switching speed of an IGBT. The irradiation has been shown to be capable of reducing the fall time from 4.51 to 0.786 μs. The fall time decreases when increasing the irradiation dose despite of the epitaxial layer thickness. Though the fall time increases when increasing the epitaxial layer thickness,there is no obvious difference between the ratios of the

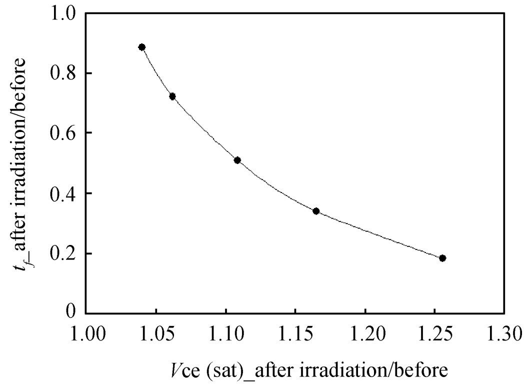

Fig. 6. Trade-off curve between the forward voltage drop and the fall time of an IGBT.

fall time after irradiation to those before irradiation for different epitaxial layer thicknesses.

The increase in the switching speed of the IGBT is accompanied by an increase in the forward voltage drop. The trade-off curve between the forward voltage drop and the fall time of an IGBT shows that the IGBT devices exhibit the unique feature: they are able to continuously adjust the switching speed and the forward voltage drop without affecting other device parameters.

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