Numerical and Experimental Study of Localized Lifetime Control LIGBT by High Dose He Ion Implantation

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Abstract: A high speed LIGBT with localized lifetime control by using high dose and low energy helium implantation(LC-LIGBT) is proposed. Compared with conventional LIGBTs, particle irradiation results show that trade-off relationship between turn-off time and forward voltage drop is improved. At the same time, the forward voltage drop and turn-off time of such device are researched, when localized lifetime control region place near the p^+-n junction, even in p^+ anode. The results show for the first time, helium ions, which stop in the p^+ anode, also contribute to the forward voltage drop increasing and turn-off time reducing.

Key words: LIGBT; localized lifetime control; helium ion implantation

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1 Introduction

Lifetime engineering is a powerful method to increase carrier recombination, particularly in power devices, increasing switching performances. Low carrier lifetime in silicon increases the switch speed of power devices with ambipolar transport by shorting the devices turn-off time. The forward voltage drop increases during decreasing lifetime, so there is a tradeoff between turn-off time and forward voltage drop. An earlier study shows that by localized lifetime control, an improved tradeoff could be achieved between turn-off time and forward voltage drop in power devices[1~3]. On the other hand, the integration in single chip of discrete power devices with logic circuit for smart power ICs fabrication requires a fine localized lifetime control in both lateral and vertical dimensions.

Recently, a method of localized lifetime control in submicron size has been reported[4,5]. It is the use of voids formed by high dose and low energy helium implantation and subsequent thermal process to control localized lifetime in silicon. Voids in silicon introduce mid bandgap traps providing a powerful method to control localized lifetime. Lower lifetime region can be obtained within a submicron tolerance. The method has been used in vertical power devices for improving their performances[6,7].

Localized lifetime control LIGBTs by high dose and low energy helium implantation (LC-LIGBT) is proposed in this paper. The localized lifetime control technique for LIGBT in SPIC by irradiating helium ions through normal mask has been experimentally studied. Compared with conventional LIGBTs, the irradiation results show that trade-off relationship between turn-off time and

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forward voltage drop has been improved.

2 Structures and mechanism

The cross section view of 600V high speed LIGBTs with localized lifetime control on 20μm epitaxial layer that had been grown on p-type silicon wafers is shown in Fig. 1. The structure is constructed by using a void layer (localied lifetime control region layer) located near anode junction. The void layer is formed by helium ions implantation at 300keV of energy and $5\times10^{16}\mathrm{cm}^{-2}$ of dose, by thermal annealling. The Δ is the distance from the anode junction. When the localized lifetime control region is at anode junction, the Δ equates to zero. While it is in p^+ region or in n region near anode junction, the Δ is negative or positive.

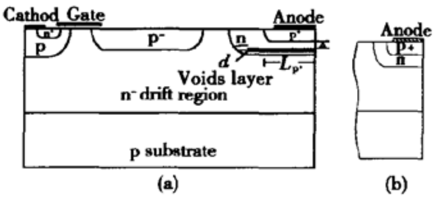

Fig. 1 (a) Localized lifetime controlled LIGBT structure; (b) Conventional LIGBT structure The cathode region is the same as (a).

High dose helium implantation in silicon causes the formation of voids without introducing any impurity or contamination and that the steps required are fully compatible with wafer processing. The value of solid solubility of noble gas in silicon is less than $10^{16}\mathrm{cm}^{-3}$. When silicon implanted with over $10^{16}\mathrm{cm}^{-3}$ helium ions is annealed at 700℃ or above, the helium forms bubbles and then diffuses out leaving voids. Different from the metals, when helium evaporates, voids are left in the silicon crystal and they are stable at a fixed temperature. The DLTS measurement results show that two deep energy levels are located at the middle of band gap in void layer. The first is for electrons, $E_C - E_{T1} = 0.55\mathrm{eV}$, and the second is for holes, $E_{T2} - E_V = 0.45\mathrm{eV}$[8]. They are shown in Fig. 2.

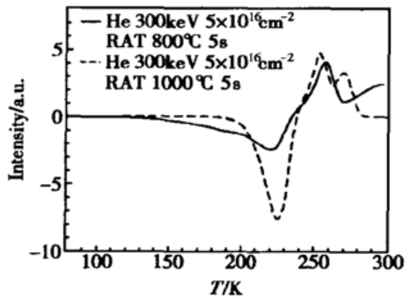

Fig. 2 DLTS measurement results

A void layer in power devices is an ideal localized lifetime killer. The method has some advantages comparing with traditional methods. (1) The void layer is quite stable during thermal treatment even over 1200℃ for 5h, so the method is well compatible with the standard fabrication of SPIC. (2) The void layer can strongly increase the recombination centers in devices, which value of recombination lifetime being obtained by measurement on transistors is 10~ 20ns. Size of the void layer is less than 0.5μm in depth and width.

Most of the previous works[9, 10] on optimization of localized lifetime control in conduction power devices suggest that the optimum location should be close to the anode junction or in deep inside the n-drift region. In the case of localized lifetime control region is placed in n-drift region, the optimum position has been discussed in our previous work[11]. Note that with few lifetime killing centers, low lifetime region recombination centers could become saturated, rendering them nearly transparent. It is clear that higher recombination rate region is located around the middle of n-base of the structure. This explains that the proper location of lower carrier lifetime layer, perpendicular to the current flow by the stored charges in middle region of n-base, would promote the considerable reduction of turn-off time but the slight increase in the on-state voltage drop. The slight increasing in the on-state voltage drop would come from the less reduction of electron concentration at the highest recombination rate layer because of the electron diffusion current at very narrow width of this layer. It means that a higher diffusion length of electron can contribute to the minimum V_F even though a wider width of the highest recombination rate in the middle of the n-base.

In this experiment, the localized lifetime control region is near anode junction. Influence of localized lifetime control region position has been numerically and experimentally analyzed in this work. There are two means to reduce the minority carrier concentration near the anode junction, one is to reduce excess carrier lifetime near the anode junction, which can be attained by such a method as the bombardment of the silicon wafer with high energy particles. The other is to reduce the hole injection efficiency from the p^+ type layer to the n type layer.

To confirm the effects of injection efficiency for the LC-LIGBT as compared to the conventional LIGBT and SA-LIGBT, the carrier distributions are calculated by using MEDICI. Three cases, in which the localized lifetime control region is at p^+-region, at anode junction, or n region, are discussed.

At the on-state, holes inject into the n-base region. The holes' profile under localized and unloaclized lifetime control is shown in Fig. 3. The holes' concentration is depended upon the local of the lower lifetime region. The Δ is the distance from p^+ n junction at the anode.

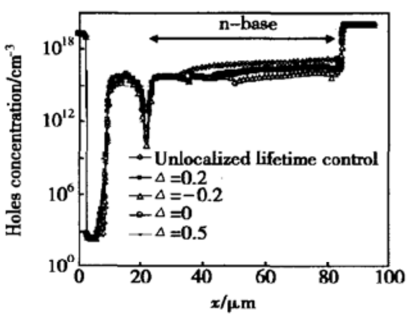

Fig. 3 Holes profile in base region

When void layer is located near the p^+-n junction, even in p^+ anode, we also found that forward voltage drop and turn-off time have been changed. Results are different from other primary works[1, 12]. Here, we explain them by two physical effects.

Under this condition, the deep energy of the void layer acts as traps. The quasi-Fermi energy for holes E_{FP} is above the E_{T1}. When density of donor deep energy is large, most of holes will transfer on the donor deep energy. At the same time, because E_{FP} is above E_{T1}, holes on the E_{T1} do not whole ionize. Then holes' concentration p_0 at p^+ n junction is:

$$p_0 = N_A - \frac{N_T}{1 + g_D \exp\left[\frac{E_F - E_{T1}}{kT}\right]} \quad (1)$$

where g_D is a degenerate factor, and N_T is the density of state on E_{T1}; N_A is impurity concentration in emitter. From equation (1), we can find that concentration of holes near the p^+ n junction has been reduced.

For the more, the excess holes' profile in base can be given as follow:

$$\Delta p(x) = p_0 \frac{\sinh[(W_B - x)/L_A]}{\sinh(W_B/L_A)} \quad (2)$$

where L_A is ambipolar diffusion length, and W_B is width of n-base. With decreasing of concentration of hole p_0 at p^+ n junction, the total of excess holes in n-base is reduced. As results, the conductional module is decreased and forward voltage drop is increased.

Meanwhile, the holes injection efficiency will be decreased when the lifetime controlled region is near the p^+ n junction. Based on BJT theory, the injection efficiency of emitter junction is

$$\gamma = \frac{1}{1 + G_B/G_E} \quad (3)$$

where

$$G_B = \int_0^{W_B} \{[N_B + \Delta p(x)]/D_B\} \mathrm{d}x$$

$$G_E = N_E L_E / D_E$$

and N_B is the concentration of n-base, D_B is diffusion coefficient, N_E, L_E, and D_E separately is hole concentration, diffusion length, and diffusion coefficient of minority carriers in emitter region. Then common-emitter current gain β is

$$\beta = \frac{1}{1 - \beta^* \gamma} \quad (4)$$

where β^* is transport coefficient in n-base.

Based on IGBT theory, the total current I is depended upon MOSFET's current I_{mos} in IGBT.

$$I = (1 + \beta) I_{mos} \quad (5)$$

The forward voltage drop V_F of LIGBT can be calculated according to equation(6).

$$V_F = V_{BE} + I_{MOS}(R_{mod} + R_{ch}) \quad (6)$$

where V_{BE} is voltage drop of p^+ n (BE) junction; R_{ch} is resistance of MOS channel and R_{mod} respectively is

$$R_{mod} = \frac{1}{qA}\int_0^{W_B} \frac{dx}{\mu_n(x) n(x,t) + \mu_p(x) p(x,t)} \quad (7)$$

From equation (4) to (7), it can be found that with the hole injection efficiency decreasing, the total current of LIGBT will be reduced. In other word, the forward voltage of LIGBT is enlarged when the total current is the same as that of conventional.

When the lower lifetime region is near p^+ n junction, recombination current at the p^+ n junction is

$$I_{GR} = \frac{qA\, dp_0}{2\tau_{He}} \quad (8)$$

where τ_{He} is lifetime of localized lifetime controlled region, d is the thickness of localized lower lifetime region, and A is the area of the device. According to the non-quasi-static (NQS) approach, total excess carriers Q in n-base is

$$Q = qp_0 A L_A \tanh(W_B/2L_A) \quad (9)$$

From equations(8) and(9), I_{GR} can be rewritten as:

$$I_{GR} = \frac{Q}{2\tau_{He} L_A \tanh(W_B/2L_A)} = \frac{Q}{\tau'} \quad (10)$$

here, the τ' is defined as $\tau' \equiv 2\tau_{He} L_A \tanh(W_B/2L_A)/d$. The total electron current at the emitter include back-injection current and recombination current of localized lower lifetime region at the p^+ n junction. The excess carrier charges in the base are decayed by the recombination of the localized lower lifetime region, and the recombination in the base as well as the back-injection into the emitter. So the effective lifetime τ_{eff} is given by

$$\tau_{eff} = \frac{\tau' \tau_{HL}}{\tau' + \tau_{HL}} \quad (11)$$

where τ_{HL} is lifetime in n-base under high-level injection. By using the method of Ref. [9], turn-off time t_{off} is obtained:

$$t_{off} = \tau_{eff} \ln \frac{10 + \dfrac{I_{AO} I_{no} \tau_{eff}}{4D_A (qAn_i)^2}}{\dfrac{1+\beta}{\beta}(1 - \Delta W_B/W_B)^2 + \dfrac{I_{AO} I_{no} \tau_{eff}}{4D_A (qAn_i)^2}} \quad (12)$$

where I_{AO} is static anode current, I_{no} is back-injection current, ΔW_B is the change of base width after excess carriers redistributed during off-cycle, D_A is ambipolar diffusion coefficient.

From above analysis, it is clear that turn-off time of LIGBT, at which localized lower lifetime region is near the p^+ n junction, has been reduced.

However, our numerical results showed helium ions, which stop in the p^+ anode, also contribute to the increasing of forward voltage drop and reducing of turn-off time. From Figs. 4 and 5, it can be found when localized lifetime control region is in the p^+ anode near the p^+ n junction, V_F increases prominently and it is the highest one, but t_{off} is not the shortest one. When lifetime control region is at the p^+ n junction or in buffer layer, the V_F is almost the same, and they are smaller than that of devices located in p^+ anode. But when $\Delta = 0$, meaning lifetime control region is at the p^+ n junction, the shortest t_{off} can be found.

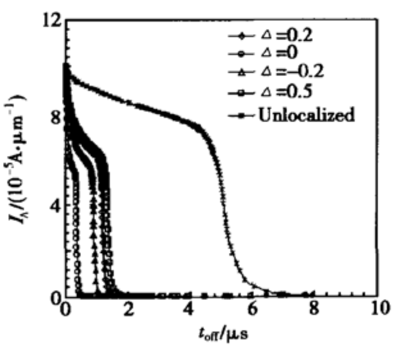

Fig. 4　Turn-off curves of 600V LIGBTs

The trade-off relationships are shown in Fig. 6. It also indicates that the He ion implantation lo-

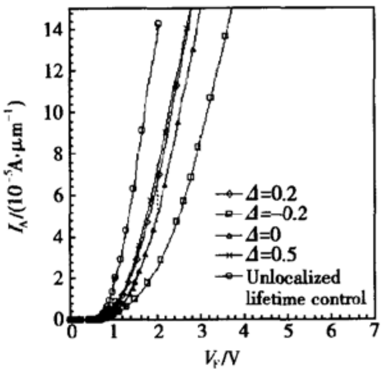

Fig. 5 Forward voltage drop of 600V LIGBT

calized lifetime control technology is suit for LIGBT, and its t_{off}-V_F trade-off relationship is superior to that of devices using unlocalized lifetime control. The forward voltage drop can be reduced 0.4 ~ 1V at the same turn-off time. When the forward voltage drop is low (< 2.5V), the relationships of both localized and unlocalized lifetime control devices are almost same. When the forward voltage drop is higher than 2.5V, He ion localized lifetime control shows its advantage over the unlocalized lifetime control.

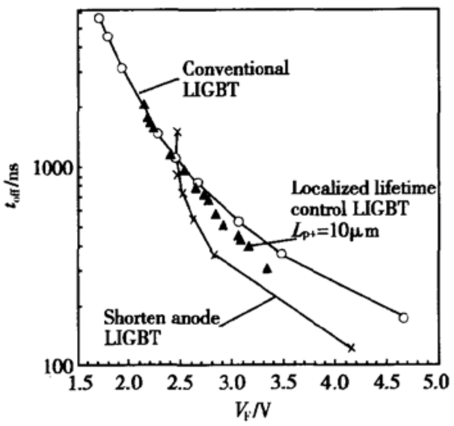

Fig. 6 Trade-off relationship (t_{off}~ V_F) of LIGBT

It is shown that the device performance change is very sensitive to location of helium irradiation. In order to show advantage of LC-LIGBT, a conventional LIGBT, LDMOS with same n-drift and cathode/source region also have been fabricated on the same wafer.

3 Experimental results

We fabricated 600V LIGBTs with localized lifetime controlled on 20μm epitaxial layer that had been grown on p-type 〈100〉 silicon wafers. After the p body and n buffer layer had been formed, the low energy and high dose helium ion implantation was made. There, about 1 μm thickness oxide and Si_3N_4 layer had been used as a mask during helium ions implanting. The void layer had been formed in the anode region by helium ions implantation at an energy of 300keV and a dose of $5\times10^{16}cm^{-2}$, and by a thermal process at 1050℃ for 30min in N_2. After this step, p^+ anode and n^+ cathode were formed by a standard process.

The n-buffer layer was 1.5μm thick and the depth of p^+ anode/n-buffer junction was 0.8μm. The void layer was located in the n-buffer, 0.7μm from the p^+ anode/n-buffer junction and just under the anode. The thickness of void layer was about 0.3μm. The void layer works as a lifetime killer in the devices.

The static and dynamic characteristics of the device with localized lifetime controlled region are given at room temperature. The 5V forward voltage is observed at $50A/cm^2$ current density in LC-LIGBT with 15V gate voltage and the turn-off time of the devices on the dynamic state is less than 135ns. The experimental results of I-V and turn-off characteristics of LC-LIGBT are shown in Fig. 7(a) and Fig. 8(a). The turn-off measurement was carried out at 300K applying 220V external voltage and switching off with $50A/cm^2$ current density.

For the conventional LIGBT the forward voltage drop is 2.1V and turn-off time is over 5.16μs. While for the conventional LDMOS, the forward voltage is higher than 22.5V, the turn-off time is less than that of LC-LIGBTs and it is 26ns. They are shown in Fig. 7 and Fig. 8.

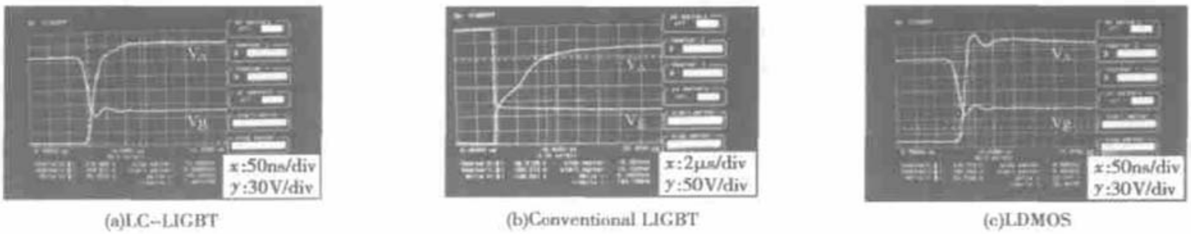

Fig. 7 Turn-off characteristics of LIGBTs and LDMOS The measurement was carried out at 300K applying an external voltage of 220V and switching off a current density of $50A/cm^2$.

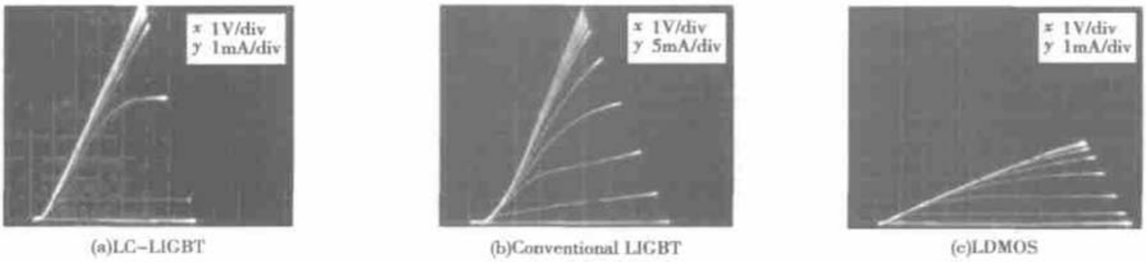

Fig. 8 *I*-*V* characteristics of LIGBTs and LDMOS Gate voltage steps are 1V.

At on-state, the low lifetime will reduce the amount of hole injection from p-type layer to n-type layer. However, forward drop increases relatively little because the low lifetime region is thin and oriented perpendicular to the current flow.

During the off cycle, the current decreases to leakage current value, while the supply voltage appears as the collector as a forward blocking voltage, and is supported by a depletion region extending from the p-base in n-base. The existence of the depletion region during the off-state is crucial in understanding the advantage of localized lifetime control. The tail in the current turn-off transient is determined by carrier recombination in the undepleted portion of n-base, so that a low carrier lifetime in this region will lead to a short turn-off time, and recombination centers in the depleted portion have minimal effect on turn-off. Therefore, maximum localized lifetime killer should be placed within undepleted region.

The void layer reduces localized recombination time, therefore the turn-off time. In fact, the dynamic characteristics are largely improved by the use of localized lifetime controll and the static characteristic is not influenced further. It gives better trade-off because it reduces the value of trade-off to 52% of conventional LIGBT at same blocking voltage.

4 Conclusion

Void formation is the advanced lifetime control method stable for huge thermal, budget and applicable in any step of device fabrication so that it improves lifetime engineering possibilities in power integrated circuit with respect to conventional lifetime control methods. A high dose helium ion irradiation has been used in LIGBT. The experimental results show particularly advantages in LIGBT where the presence of a well localized carrier recombination region in n-buffer layer improves device performances. It shows better trade-off relationship than conventional LIGBT can be obtained by using the lifetime control technique. The lifetime control technique is adapted for LIGBT in SPIC in order to realize the high performance.

At the same time, the forward voltage drop and turn-off time of such device have been researched, when localized lifetime control region was placed near the p^+-n junction, even in p^+ anode. The results show for the first time, helium ions, which stop in the p^+ anode, also contribute to forward voltage drop increasing and turn-off time reducing.

References

[1] Baliga B J. Comparison of gold, platinum, and electron irradiation for controlling lifetime in power rectifiers. IEEE Trans Electron Devices, 1977, 24(6): 685

[2] Temple A K. Optimizing carrier lifetime profile for improved trade-off between turn-off time and forward drop. IEEE Trans Electron Devices, 1983, 30(7): 782

[3] Antonio M C, Robert P L. Localized lifetime control in insulated-gate transistors by proton implantation. IEEE Trans Electron Devices, 1992, 33(11): 1667

[4] Seager C H, Myers S M. Electrical properties of He-implantation produced nanocavities in silicon. Phys Rev B, 1994, 50(4): 2458

[5] Raineri V, Fallica G. Gettering of metals by voids in silicon. J Appl Phys, 1995, 79(6): 3727

[6] Raineri V, Saggio M. Voids in silicon power devices. Solid-State Electron, 1998, 42(12): 2295

[7] Saggio M, Raineri V. Innovative localized lifetime control in high speed IGBT's. IEEE Trans Electron Devices, 1997, 18(7): 333

[8] Raineri V, Fallica G. Lifetime control in silicon devices by voids induced by He ion implantation. J Appl Phys, 1996, 79(12): 9012

[9] Li Zhaoji, Zhang Ming, Yang Jian, et al, Analytical turn-off current model for type of conductivity modulation power MOSFETs with extracted excess carrier. Solid-State Electron, 2000, 44(1): 1

[10] Li Zhaoji, Du Juan. Turnoff transient characteristics of complementary insulated-gate bipolar transistor. IEEE Trans Electron Devices, 1994, 41(12): 2468

[11] Fang Jian, Li Zhaoji, Li Hongyan, et al, A transport model for conductivity modulation power devices with localized lifetime control by low energy He ion implantation. Acta Electronic Sinica, 2001, 29(8): 1072(in Chinese) [方健, 李肇基, 李鸿雁, 等. 低能 He 注入局域寿命控制电导调制型功率器件输运模型. 电子学报, 2001, 29(8): 1072]

[12] Fang Jian, Li Zhaoji, Li Hongyan, et al. High speed LIGBT with localized lifetime control by using high dose and low energy helium implantation. ICSICT, 2001: 174

低能量 He 离子注入局域寿命控制 LIGBT 的实验研究

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摘要: 提出了一种采用低能量大剂量 He 离子注入局域寿命控制的高速 LIGBT, 并对其进行了实验研究. 粒子辐照实验结果显示与常规的 LIGBT 相比较, 该器件的关断时间和正向压降的折中关系得到了改善. 同时研究了当局域寿命控制区位于 p^+-n 结附近, 甚至在 p^+ 阳极内时, 该器件的正向压降和关断时间. 结果显示当局域寿命控制区在 p^+ 阳极内时, 仍然对关断时间和正向压降有影响.

关键词: LIGBT; 局域寿命控制; He 离子注入

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