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Technical Note

Trade-off between the Kirk effect and the breakdown performance in resurfed lateral bipolar transistors for high voltage, high frequency applications

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Abstract

The trade-off between the breakdown performance and the Kirk effect has been evaluated and compared among conventional bipolar transistors and resurfed lateral bipolar transistors. It was demonstrated that the traditional conflict of differing requirements on W_c and N_c by the breakdown performance and the Kirk effect can be eased by incorporating the resurf principle. Comparative studies have been carried out between the optimized devices with breakdown voltages from 20 to 40 V. It is shown that for an identical breakdown voltage, the high-current-level performance of the resurfed devices can be significantly improved by incorporating a gradually doped collector region. This further leads to a significant increase in the cut-off frequency without degrading the breakdown performance. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Bipolar transistor; Silicon-on-insulator; Resurf principle; Kirk effect; Breakdown voltage

1. Introduction

In recent years, thin film silicon-on-insulator (TFSOI) technology has been considered as a competing candidate for BiCMOS circuits, due to the ease of isolation of devices. Significant progress has been made in developing power MOSFETs on thin SOI with the main focus on the trade-off between the on-resistance and the breakdown voltage [1]. As for applications to bipolar transistors, thin SOI is also preferred because of the lower parasitic capacitance. Considerable attention has been devoted towards the development of high-performance, low-voltage lateral bipolar transistors (LBTs) on thin SOI [2–4]. However, the potential for high frequency, high voltage LBTs on thin SOI has not been addressed. Furthermore, bipolar transistors are fundamentally different from MOSFETs due to Kirk effect and its influence on the device frequency performance and current capability [5]. For high voltage devices, a trade-off has to be made on designing the collector width and concentration, due to the conflicting requirements on the collector design by the breakdown voltage and the critical current density at which Kirk effect takes place.

Previously, we have reported a 60 V MOSFET on thin SOI [6]. A technique was proposed to achieve a graded doping profile, which has been used to reduce the switching loss significantly. In this paper, the proposed technique is further applied to resurfed LBTs on thin SOI. The influence of resurf effect [7] on the trade-off between the Kirk effect and the breakdown performance has been analyzed in LBTs on thin-film SOI (TFSOI LBTs). Through two-dimensional numerical simulations, the effects of buried oxide thickness and the collector doping profile on the trade-off are evaluated. Comparative results are also presented on the trade-off in conventional bipolar transistors and resurfed devices.

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2. Device structure and considerations

The conventional devices are modeled with a one-dimensional structure. For each breakdown voltage (BV_{ceo}), width (W_c) and doping concentration (N_c) of the collector region are optimized to get the highest critical current for the Kirk effect. For the TFSOI LBTs, two cases have been considered: uniformly doped collector (UDC) and gradually doped collector (GDC). The simplified cross-section of the TFSOI LBT structure under study is depicted in Fig. 1(a). For the UDC LBTs, W_c, N_c as well as the thickness of the buried oxide layer (t_{BOX}) are optimized. Fig. 1(b) shows the doping profile in a 40 V GDC LBT. The GDC can be achieved through a masked implantation of phosphorous ions followed by a drive-in step [6]. The dose and drive-in condition are optimized using the process simulator TSUPREM-6.4 [8]. All other parameters are defined using TMA–Medici [9]. Uniform doping concentration is used for base and emitter regions in all the devices. All the devices considered herein have the same B–C junction area of 1 μm × 0.16 μm.

To avoid the difference in BV_{ceo}, caused by different values of current gain (β), devices have been carefully designed to show an identical β. Sufficiently high concentration is also chosen for the base region to avoid base punch-through.

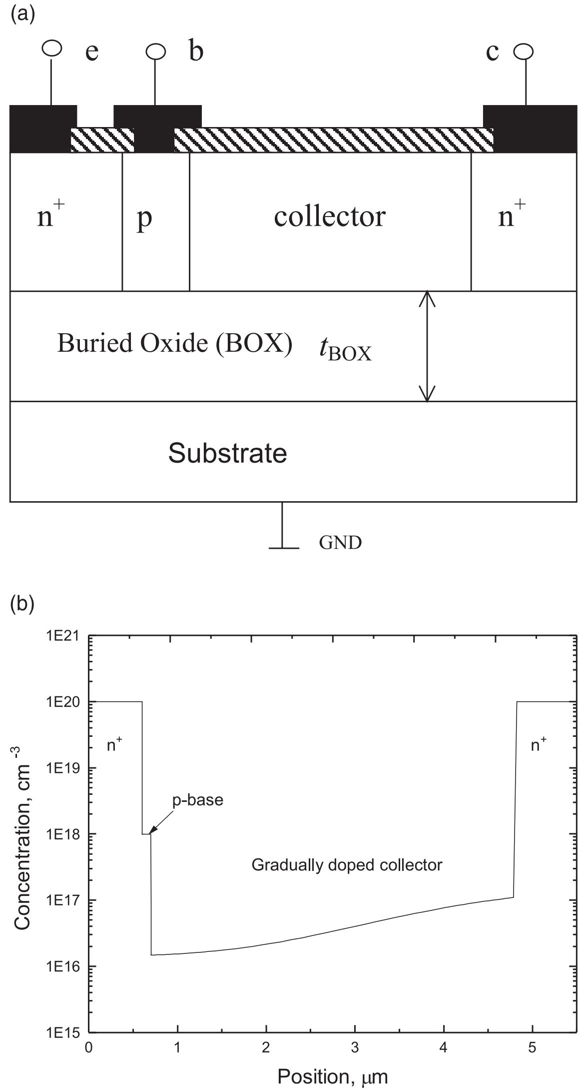

Fig. 1. (a) A simplified structure of a resurfed lateral bipolar transistor on thin-film SOI and (b) doping profile in a 40 V resurfed device with a GDC.

3. Simulations and discussions

The current gains at different injection levels and breakdown voltage (BV_{ceo}) have been simulated for both the resurfed devices and the conventional devices. The value of collector current (I_{cr}), at which current gain falls to half its value at low-level injection, is used to evaluate the Kirk effect. To demonstrate the effect of buried oxide thickness (t_{BOX}) on the trade-off between the breakdown performance and the Kirk effect, BV_{ceo} and I_{cr} are plotted in Fig. 2 for the resurfed devices (UDC LBTs) and the conventional devices (1-D model). For each curve, N_c ranges from 2×10^{15} to 3.5×10^{16} cm^{-3}. In a resurfed device, there is an optimum collector doping concentration for the maximum breakdown voltage. Since I_{cr} is a function of N_c, the curves for 0.5 and 1 μm BOX in Fig. 2 show a similar trend as the dependence of breakdown voltage on the dose in the drift region for the SOI MOSFET [1]. The buried oxide thickness influences the vertical electric field in the resurfed devices. As a result, the collector depletion layer is also affected. When t_{BOX} increases, the vertical electric field along the SOI/BOX interface decreases, and the resurf principle becomes less dominant. As can be observed in Fig. 2, the LBTs with a thicker buried oxide layer tend to perform like conventional devices. With a reduction in buried oxide thickness, the vertical electric field becomes stronger, and a higher collector doping concentration is required to distribute the peak electric field symmetrically at the two ends of the collector region. Therefore, as shown in Fig. 2, I_{cr} corresponding to the maximum breakdown voltage increases with the decrease of buried oxide thickness. Due to the influence of the buried oxide, the conflict over the different requirements on W_c and N_c by the breakdown performance and the Kirk effect is eased. It is also observed (Fig. 2) that, in the case of the LBTs, different values for the breakdown voltage can be obtained for the same I_{cr}. Therefore, it is possible to optimize the breakdown voltage and the critical current independently with the LBTs.

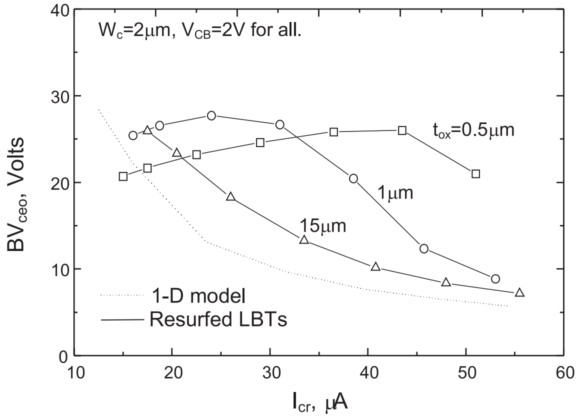

Fig. 2. Effect of the buried oxide thickness on the trade-off between breakdown performance and the Kirk effect.

A further comparative study has been carried out between the resurfed devices and the conventional ones, which are optimized for BV_{ceo} ranging from 20 to 40 V. The physical parameters for the optimized devices of each group are listed in Table 1. Also given are the simulated I_{cr} and BV_{ceo} of these devices. As can be seen in Table 1, with the breakdown voltage increasing from 20 to 40 V, N_c needs to decrease from 1×10^{16} to 2×10^{15} cm^{-3} for the conventional devices. While in the UDC LBTs, as the thickness of the buried oxide layer is also increased, N_c does not have to be significantly reduced. Therefore, the difference in I_{cr} of conventional devices and UDC LBTs increases with the breakdown voltage.

As shown in Table 1, the best trade-off is demonstrated by the GDC LBTs. This can be explained by Fig. 3(a) and (b), where the surface electric field distribution in the 40 V UDC LBT and the GDC LBT is plotted at different collector currents. In an UDC LBT, the depletion layer extends only partly into the collector region when no current flows through the region (curve "a" in Fig. 3(a)). Increasing the collector current results in reducing the net space charge density in the collector region, causing the depletion layer to extend into the collector region until it fills the whole collector region (curve "b" in Fig. 3(a)). Any further increase in collector

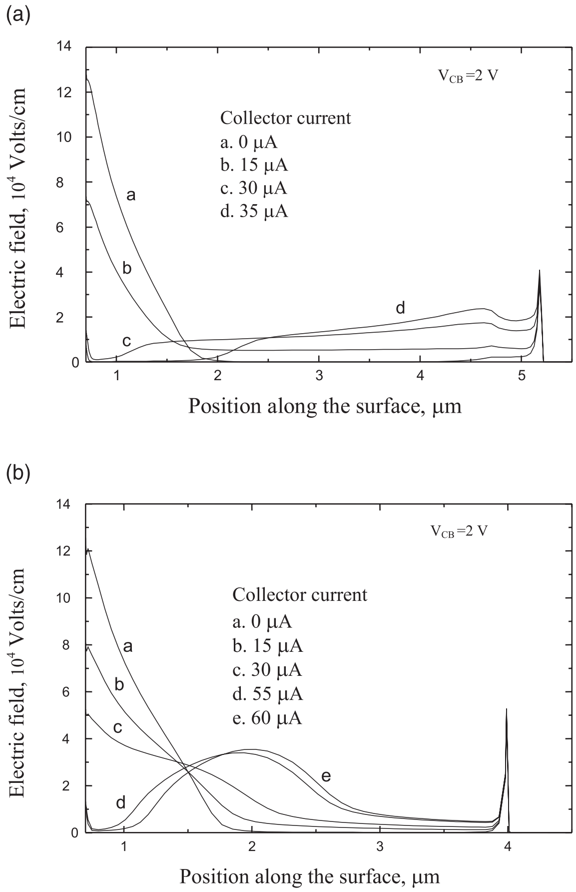

Fig. 3. Surface electric field profiles at different collector current levels in (a) UDC LBT and (b) GDC LBT.

Table 1
A summary of physical parameters and performance of the optimized devices

	BV_{ceo} (V)	I_{cr} (μA)	W_c (μm)	N_c (cm^{-3})	t_{BOX} (μm)	f_T (GHz)
1-D model	21	30	1.5	1×10^{16}	–	7.5
	32	13.2	2.5	5×10^{15}	–	3.3
	41	6.25	3.3	2×10^{15}	–	2.6
UDC LBT	24	50.5	2	3×10^{16}	0.38	9.7
	31	29	3	2×10^{16}	0.7	7.8
	40.5	18.7	4.5	1.7×10^{16}	1.1	6.1
GDC LBT	23	65	1.7	1.5×10^{16}–7.5×10^{16}	0.38	10.0
	31	50	2.5	1.5×10^{16}–1.1×10^{17}	0.38	9.7
	41	40	3.3	1.5×10^{16}–9×10^{16}	0.6	8.8

current causes the peak electric field to shift from the base end to the collector end (curve "c", "d" in Fig. 3(a)). The collector bias is now supported by n^-/n^+ junction, and the current induced base width begins to increase.

In the GDC LBT, since the collector doping concentration at the base end is similar to that in the UDC LBT, initially, the two electric field profiles are identical (curve "a" in Fig. 3(a) and (b)). With an increase of the collector current, the peak electric field also decreases due to the extension of the depletion layer. However, in the case of GDC LBT, to compensate the same amount of increase in mobile charges caused by the increase in the collector current, the depletion layer extends less into the neutral collector than in the UDC LBT. This enables the peak electric field to remain at the base end even at a collector current of 30 μA (curve "c" in Fig. 3(b)). The collector bias in the GDC LBT is supported by the base/collector junction until the collector current is larger than 55 μA (curve "d" in Fig. 3(b)). Base-widening occurs for collector current higher than this level. However, since the collector doping concentration increases towards the n^+ collector, the injected-carrier density should also increase with the base widening. As a result, in the case of a gradually doped collector region, the increase in the current-induced base width is less for the same change (5 μA from curves "d" to "e" in Fig. 2(b)) in the collector current in comparison to the case of uniformly doped collector (curves "c" to "d" in Fig. 3(a)).

In Fig. 4 is shown the surface electric field at breakdown in the resurfed GDC LBT with the doping profile shown in Fig. 1(b). A non-resurfed structure is also formed by simply removing the buried oxide and the surface oxide layers in the resurfed GDC LBT. These two structures are used only for the demonstration of the influence of the resurf effect. Therefore, no further optimization has been made for the non-resurfed structure. The two structures show an identical critical current density for the Kirk effect because they have the same doping profile in the GDC region. However, as can be observed in Fig. 4, the GDC region is fully depleted in the resurfed GDC LBT, yielding a breakdown voltage of 41 V. In contrast, due to the absence of a vertical electric field, the GDC region cannot be fully depleted in the non-resurfed structure, causing a much lower breakdown voltage of 12 V. This suggests that the collector doping concentration is too high for the non-resurfed structure. To achieve an identical breakdown voltage, a lower doping concentration should be used in the non-resurfed structure in comparison to the resurfed LBT.

In Ref. [10], it has been observed that in comparison to the uniformly doped collector, a gradually doped collector in bulk silicon shows a higher current capability without degrading the breakdown voltage. However, compared to a bulk device, the GDC profile in the resurfed SOI device is independent of the concentration in the n^+ collector region, and can be easily achieved/modified by changing the implantation dose and drive-in conditions. Furthermore, for an identical breakdown voltage, presence of the resurf effect allows for a higher doping concentration in the GDC region. This leads to a higher current capability in the case of a resurfed LBT.

The current gains have also been simulated at different frequencies. Cut-off frequencies (f_T) are extracted corresponding to unit current gain at an emitter–collector bias of 2 V. Values of f_T are compared in Table 1 for device breakdown voltages. Due to suppression of Kirk effect, the GDC LBTs have the highest f_T in each group. The cut-off frequencies at 2 and 20 V against the collector currents are compared in Fig. 5 among the three 40 V devices. For the 1-D structure, the cut-off

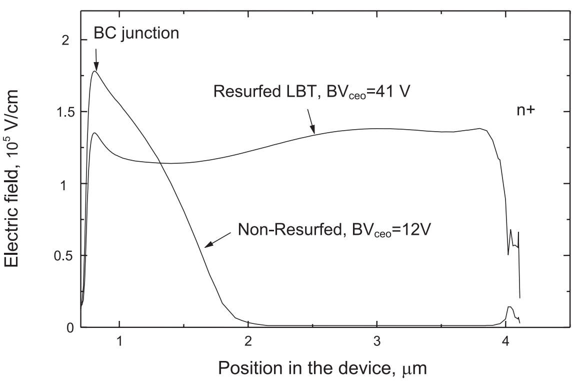

Fig. 4. A comparison of electric field profiles at breakdown voltage in resurfed and non-resurfed devices with a GDC.

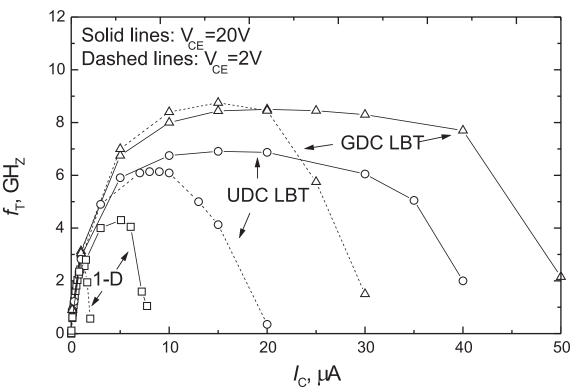

Fig. 5. A comparison of cut-off frequency vs. collector current among 40 V devices.

frequency falls off at very low collector current because of the Kirk effect. In the case where Kirk effect is dominant, increasing the collector bias can lead to a higher critical current density. Therefore, the cut-off frequency increases from 2.6 to 4.3 GHz corresponding to collector bias increase from 2 to 20 V. In the case of UDC LBT, the Kirk effect is suppressed but is still a major factor for the fall-off of the cut-off frequency at high current levels, especially at 2 V. In the GDC LBT, the current range over which the cut-off frequency is at its highest value is much wider. This reveals that the Kirk effect is no longer a primary factor that limits the cut-off frequency. As a result, the maximum achievable cut-off frequency does not increase with the collector bias. Instead, it slightly decreases because of the wider depletion layer in the collector at 20 V.

4. Conclusion

Due to the resurf effect, a higher collector doping concentration in the TFSOI LBTs is permitted, compared to conventional devices with identical breakdown voltage. This leads to a significant increase in the critical current density for the Kirk effect in the devices. The trade-off between the breakdown performance and the Kirk effect can be further improved by incorporating a gradually doped collector region in the TFSOI LBTs. Consequently, the cut-off frequency is dramatically increased compared with the conventional devices and the resurfed LBTs with uniformly doped collectors. The result of this work paves the way to further enhance the capability of bipolar devices to operate at high voltage, high current and high frequency.

References

[1] Matsumoto S, Yoshino H. Device simulation of a thin-film silicon on insulator power metal-oxide-semiconductor field-effect transistor for structure optimization. Jpn J Appl Phys 1994;33:519–23.

[2] Edholm B, Olsson J, Soderbarg A. A self-aligned lateral bipolar transistor realized on SIMOX-material. IEEE Trans Electron Dev 1993;40(12):2359–60.

[3] Parke SA, Hu C, Ko PK. A high-performance lateral bipolar transistor fabricated on SIMOX. IEEE Trans Electron Dev Lett 1993;14(1):33–5.

[4] Shino T, Inoh K, Yamada T, Nii H, Kawanaka S, Fuse T, Yoshimi M, Katsumata Y, Watanabe S, Matsunaga J. 31 GHz f_{max} lateral BJT on SOI using self-aligned external base formation technology. IEDM, 1998. p. 953.

[5] Sze SM. Physics of semiconductor devices. New York: Wiley; 1981.

[6] Cao GJ, De Souza MM, Narayanan EMS. A high performance 60-V class lateral power MOSFET on thin film SOI with a graded doping profile in the drift region. Proc 22nd IEEE Int Semicond Conf. Romania, 1999. p. 123–6.

[7] Merchant S, Arnold E, Baumgart H, Egloff R, Letavic T, Mukherjee S. Pein. Dependence of breakdown voltage on drift length and buried oxide thickness in SOI Resurf LDMOS transistors. Proc 5th ISPSD. California, 1993. p. 124–8.

[8] TSUPREM, Two-dimensional process simulation program, Version 6.4. Technology Modeling Association, Inc. Sunnyvale, California.

[9] MEDICI, Two-dimensional device simulation program, Version 4, Technology Modeling Association, Inc. Sunnyvale, California.

[10] Ugajin M, Konaka S, Yokoyama K, Amemiya Y. A simulation study of high-speed silicon heteroemitter bipolar transistors. IEEE Trans Electron Dev 1989;36(6): 1102.