200 ℃ High-Temperature and High-Speed Operation of 440 V Lateral IGBTs on 1.5 μm thick SOI

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Abstract

This paper experimentally verifies that high-voltage lateral IGBTs fabricated on SOI of less than 5 μm exhibit high switching speed without the need for any special device design. This paper also verifies, for the first time, that thin SOI is a promising candidate for 200 ℃ high-temperature operation, because switching speed is not deteriorated at high temperature.

Introduction

Thin SOI technology is of great interest because high-voltage devices can be integrated on the same chip together with CMOS circuitry by simply using shallow trench isolation [1]. The authors have theoretically predicted [2,3] that lateral IGBTs fabricated on thin SOI exhibit high switching speed without the need for any special device design. This means that high-voltage, high-speed output devices can be fabricated on thin SOI by using the conventional CMOS processes without lifetime control, leading to a VLSI with high-voltage power devices or a system on chip.

The present paper not only experimentally verifies the above predictions but also shows, for the first time, that SOI thinner than 5 μm is a good candidate for high-temperature operation high-voltage power ICs. Power ICs that operate at 200 ℃ are frequently required in automotive and motor control applications. The authors focus on successful high-temperature operation of 440 V lateral IGBTs on even thinner SOI of 1.5 μm. The turn-off fall-time of IGBTs on 1.5 μm SOI was only 360 ns, even at 200 ℃. The advantages of 1.5 μm SOI IGBTs are clarified in this paper.

Device Fabrication

Fig.1 shows the cross-sectional view of the fabricated lateral IGBT. The SOI wafers were prepared by silicon wafer direct bonding method. The SOI layer thickness of the starting wafers ranged from 1.5 μm to 20 μm. Thick buried silicon dioxide layer of 2 μm or 3 μm was used to realize high breakdown voltages. The diffusion depth of the n-buffer was 5 μm, so that it did not reach the buried oxide layer in the case of the SOI layer thicker than 5 μm.

It should be noted that IGBTs on 1.5 μm SOI were fabricated in carefully maintained fabrication facilities, so that the surface recombination velocity was kept low and the carrier lifetimes were kept high.

IGBT characteristics at room temperature

A. Breakdown voltage

Fig.2 shows the measured breakdown voltage as a function of SOI layer thickness. Breakdown is caused by the vertical electric field around or under the n-buffer region. Thick buried oxide layer contributes to keep the vertical electric field low, resulting in high breakdown voltage. The breakdown voltages of IGBTs on 3 μm thick oxide were about 130 V larger than those of IGBTs on 2 μm oxide. IGBTs on 1.5 μm thick SOI on 3 μm oxide exhibited a 440 V breakdown voltage. For the SOI thinner than 5 μm, the breakdown voltage did not decrease and even increased as the SOI thickness decreased. This is because the n-buffer reached the oxide and the SOI thickness has only slight influence on the electric field distribution around the n-buffer [4].

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B. Forward voltage-drop

Fig.3 shows the current voltage curves of a 1.5 μm SOI IGBT. Although the effects of surface recombination were expected to be significant in IGBTs on SOI less than 2 μm thick [2], the measured current voltage relations are quite good. The forward voltage was 2.8 V at 100 A/cm^2 current density for 12 V gate voltage, and 2.4 V for 20 V gate voltage. The SOI thickness dependence of forward voltage-drop for current of 100 A/cm^2 is shown in Fig.4. The forward voltage-drop slightly increased with decreasing the SOI thickness. However, it did not depend on the buried oxide thickness and the n-buffer impurity dose.

The surface recombination velocities were estimated by comparing the data of carrier lifetime dependences on SOI layer thickness with the theoretical dependence (for example, see Fig.13 of reference[2]). The obtained velocity was 1000 cm/s. It was found that the forward voltage-drops were very high for the samples, whose surface recombination velocities were more than 2000 cm/s.

C. Switching speed

Fig.4 also shows the measured turn-off fall-time as a function of SOI layer thickness. Turn-off speed can be improved either by reducing the SOI layer thickness or by increasing the impurity concentration in the n-buffer. IGBTs with a high impurity dose n-buffer on a SOI of less than 5 μm can achieve fall-times of less than 300 ns, which are sufficiently short for a high-frequency operation of 20 kHz. It is an astonishing fact that the fall-time simply decreases without significant increase in forward voltage as the SOI layer thickness decreases from 10 μm to 1.5 μm. The reason is assumed to be as follows.

1) Actual current density flowing laterally in the SOI layer increases in inverse proportion to the SOI layer thickness. The current density of 1.5 μm SOI IGBT reaches 5000 A/cm^2 for the normal operating condition of 100 A/cm^2, which is defined by the drain current divided by the device area. Thus, most of the current flows by drift in such a high current density condition, and the amount of the stored carriers in the drift region is relatively small.

2) Electrons are injected into the n-drift region through the channel region. The channel resistance is never influenced by reducing the SOI layer thickness. However, hole current flows into the p-base mostly by diffusion under the channel region. Thus, the amount of hole current flow into the p-base is decreased as the SOI layer thickness is decreased. This effectively increases the electron injection efficiency. The effect is the same as IEGT [5], which is proposed in this meeting.

The results described so far show that thin SOI has an advantage to realize high-speed switching while the breakdown voltage and forward voltage-drop are a little sacrificed. High-frequency operation will be realized without lifetime control by using thin SOI.

High-temperature characteristics

High-temperature operation is required for power ICs applied to automobiles or motor control. The authors investigated the relations between the temperature and the IGBT characteristics.

Fig.5 shows the temperature dependence of the reverse biased leakage current. The leakage current increases as temperature increases. However, it was found that the leakage current decreases effectively as the SOI layer thickness decreases, although the magnitude of the leakage current depends on the quality of the SOI wafer. The leakage current for lateral IGBTs on 1.5 μm SOI was less than 2 nA at room temperature and 100 nA even at 200 ℃. These values were one order of magnitude smaller than those of 10 μm SOI IGBTs.

It was found that the leakage current is more than one order of magnitude smaller than the calculated value: (depletion volume) times (n_i/τ), where τ is measured from diode reverse recovery characteristics. This implies that surface generation velocity is small although surface recombination velocity is large.

Fig.6 shows the temperature dependence of forward voltage-drop in lateral IGBTs. Thin SOI IGBT had the same temperature dependence as thick SOI IGBT, although the drift region resistance is higher for thin SOI.

On the other hand, the temperature dependence of the turn-off fall-time for 1.5 μm SOI IGBTs was much weaker than that of

IGBTs on 10 μm thick SOI. Fig.7 shows the relation between the fall-time and temperature. The turn-off waveforms are shown in Fig.8. The fall-time of 1.5 μm SOI IGBTs increases by only 50 % from 25 ℃ to 200 ℃, whereas the fall-time of 10 μm SOI IGBTs at 200 ℃ is 2.5 times larger than for 25 ℃.

These results show that thin SOI is very promising for high-temperature operation. The authors further confirmed that IGBTs on thin SOI have the potential to operate even at 300 ℃.

Conclusion

Thin SOI of less than 5 μm is suitable for simple dielectric isolation of power ICs. Lateral IGBTs on such thin SOI had a sufficient breakdown voltage by using thick buried oxide layer. The forward voltage-drop was only slightly affected by decreasing SOI thickness. The switching speed exhibited significant improvement by decreasing SOI thickness. From these results, high-speed power ICs are expected to be realized on thin SOI by using the conventional CMOS processes without lifetime control. It was found that thin SOI has advantages also in high-temperature operation. This result indicates the possibility of a great extension of the application field of SOI power ICs.

Acknowledgments

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References

[1]A. Nakagawa, N. Yasuhara, I. Omura, Y. Yamaguchi, T. Ogura and T. Matsudai, "Prospects of high voltage power ICs on thin SOI", 1992 IEEE IEDM Tech. Digest, p. 229.
[2]I. Omura, N. Yasuhara, A. Nakagawa and Y. Suzuki, "Numerical analysis of SOI IGBT switching characteristics --Switching speed enhancement by reducing the SOI thickness", Proceedings of ISPSD'93, p. 248.
[3]N. Yasuhara, T. Matsudai and A. Nakagawa, "SOI layer thickness and buried oxide thickness dependencies of high voltage lateral IGBT switching characteristics", Ext. Abstracts of 1993 SSDM, p. 270.
[4]W. Wondrak, R. Held, E. Stein and J. Korec, "A new concept for high-voltage SOI devices", Proceedings of ISPSD'92, p. 278.
[5]M. Kitagawa, I. Omura, S. Hasegawa, T. Inoue and A. Nakagawa, "An injection enhanced 4500 V insulated gate bipolar transistor (IEGT) operating in a mode similar to a thyristor", 1993 IEEE IEDM Tech. Digest.

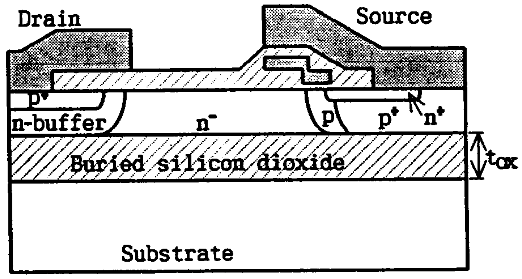

Fig.1 Lateral IGBT structure on 1.5 μm SOI.

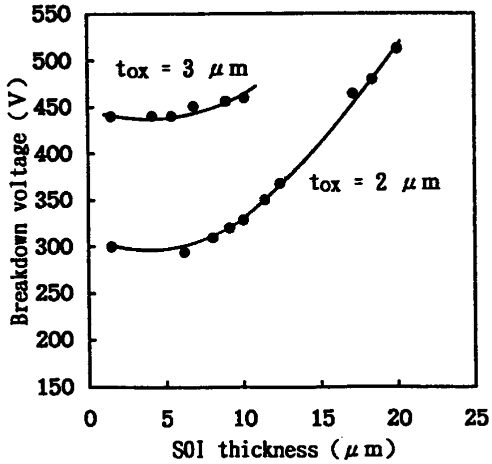

Fig.2 Breakdown voltage as a function of SOI thickness with buried oxide thickness as a parameter.

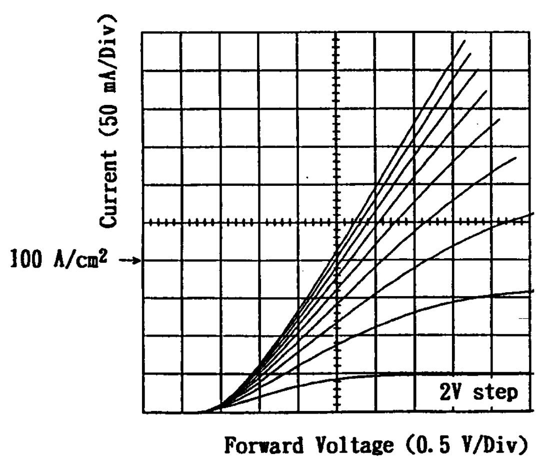

Fig.3 Current voltage curves for 1.5 μm SOI IGBT.

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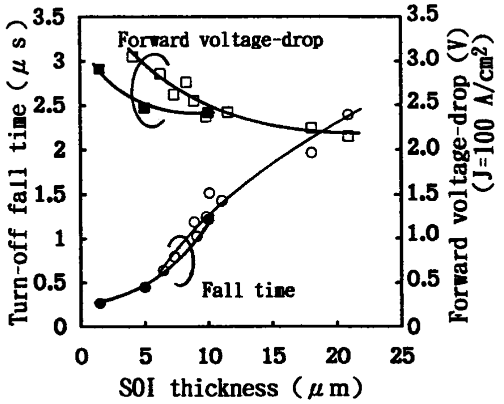

Fig.4 Turn-off fall-time and forward voltage-drop as a function of SOI thickness. Results for 2 series of samples with different histories are shown.

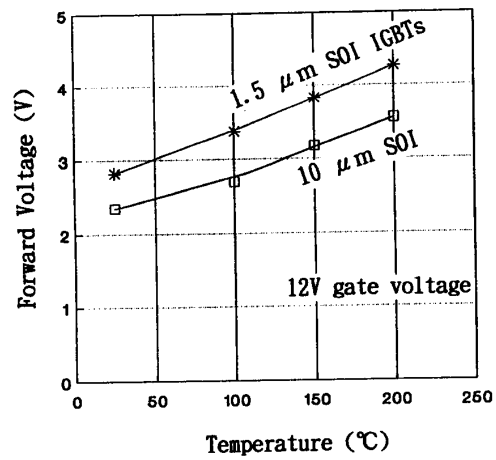

Fig.6 Forward voltage-drop as a function of temperature.

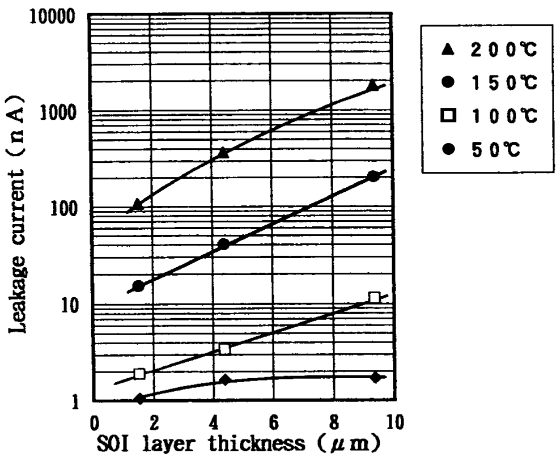

Fig.5 Reverse biased leakage current as a function of SOI thickness with temperature as a parameter.

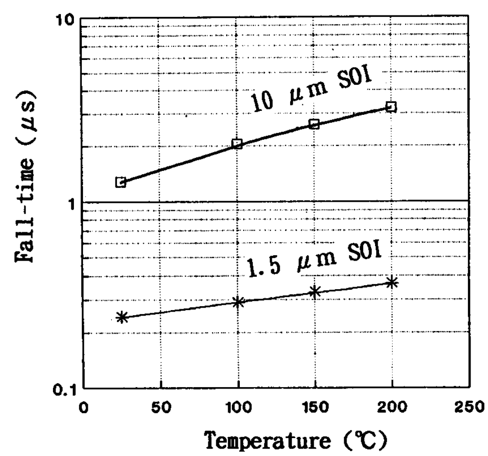

Fig.7 Fall-time as a function of temperature. Temperature dependence of fall-time for 1.5 μm SOI IGBT is small.

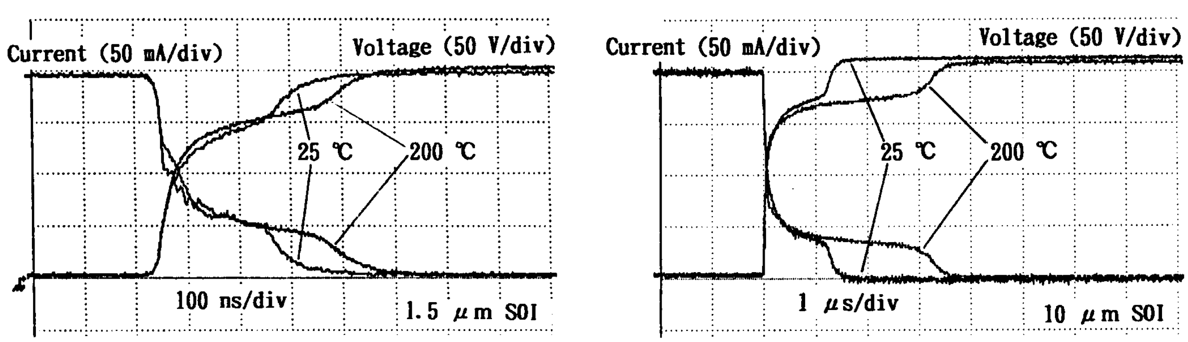

Fig.8 Turn-off waveforms for SOI IGBTs.