Research Report

Proposal of Novel Collector Structure for Thin-wafer IGBTs

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薄ウェハIGBTのための新規コレクタ構造の提案

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Abstract

A novel collector structure for thin-wafer IGBTs used in hybrid electric vehicles to make a contact resistance lower without increasing turn-off loss is proposed. This structure has a p^- Si injection layer and a p^+ Ge contact. The characteristics of a device with this new collector structure were investigated by simulation. A 1.2kV thin-wafer IGBT with the this p^+ Ge contact layer was fabricated, and its turn-off time and on-voltage were measured. No remarkable increase in turn-off time was found, in spite of a high carrier concentration in the contact layer. Moreover, the contact resistance in the collector of the proposed device was low, compared with that of the conventional device. These results demonstrate that the novel collector structure enables a low-resistivity contact without increasing turn-off loss.

Keywords
Thin-wafer, IGBT (Insulated Gate Bipolar Transistor), Contact resistance, Turn-off loss, Ge contact layer

要　旨

本研究では，ハイブリッド自動車用薄ウェハIGBTに対し，ターンオフ損失を増やすことなくコンタクト抵抗を低くする新規のコレクタ構造を提案した。この構造は，低キャリア濃度p型 (P^-) シリコン注入層と，高キャリア濃度p型 (P^+) ゲルマニウムコンタクト層を持つ。その新規なコレクタ構造を持つデバイス特性をシミュレーションにて調べた。そのp^+ゲルマニウムコンタクト層を付加した1.2kVの薄ウェハIGBTを作製し，そのターンオフ時間とオン電圧を測定した。結果として，コンタクト層のキャリア濃度が高いにもかかわらず，そのデバイスでは，ターンオフ時間の顕著な増大が認められなかった。また，従来デバイスの接触抵抗に比べ，提案構造のコレクタでの接触抵抗は低かった。これらの結果は，この構造がターンオフ損失を増大させることなく，接触抵抗を低くできることを示す。

キーワード
薄ウェハ，IGBT（絶縁ゲート型バイポーラトランジスタ），コンタクト抵抗，ターンオフ損失，ゲルマニウム接触層

1. Introduction

IGBTs are key components of an inverter for hybrid vehicles. We have developed technologies that control the local lifetime and trench gate structure of these devices to achieve low-loss.[1, 2) Recently, thin-wafer IGBTs fabricated from bulk substrates have been developed for economical reasons, the cost of bulk substrates being low compared with the epitaxial substrates used in many other IGBTs.[3, 4) However, there are some technical problems with devices fabricated from bulk substrates due to increase in the contact resistance.[5) Whereas shrinking a device chip is the most conventional way to cut cost, the resultant increase in current density raises on-state loss. In general, a higher carrier concentration in a collector for making a low-resistivity contact results in an increase in turnoff loss.

In this study, we proposed a novel collector structure for thin-wafer IGBTs to make a low-resistivity contact without increasing turnoff loss. The novel collector structure has a p^+ Ge contact layer on a p^- Si injection layer. The characteristics of a device with the collector structure were investigated by simulation. A 1.2kV thin-wafer IGBT with the p^+ Ge contact layer was fabricated, and it was verified that there is low-resistivity contact with no increase of turn-off loss.

2. Thin-wafer IGBTs

2. 1 Conventional device structure

Figure 1 shows a schematic cross-sectional view of a conventional thin-wafer IGBT. The wafer thickness, which is determined based on desired breakdown voltage, ranges from 100μm to 200μm. The IGBT is composed of an emitter, a gate, and a collector, as shown in Fig. 1(a). The collector region is also shown in Fig. 1(b), and the device characteristics can be controlled by changing the carrier concentration in the p^- Si injection layer. A schematic turn-off curve is shown in **Fig. 2**(a). Also, Fig. 2(b) schematically shows the turn-off time as a function of carrier concentration in the p^- Si injection layer. The turn-off time increases with increasing carrier concentration in the p^- Si injection layer. Thus, the carrier concentration should be minimized to reduce low turn-off loss.

2. 2 Contact resistance theory

For metal-semiconductor contacts with lower carrier concentrations, the thermionic-emmission current dominates the current transport, and the contact resistance depends only on the barrier height. For higher carrier concentrations, on the other hand, the tunneling process dominates the current transport, and the contact resistance decreases with increasing carrier concentration. Moreover, for p-type semiconductors, the barrier height depends on the energy band gap of the material. Therefore, using a narrow band gap material, such as Ge, enables a low-resistivity contact.

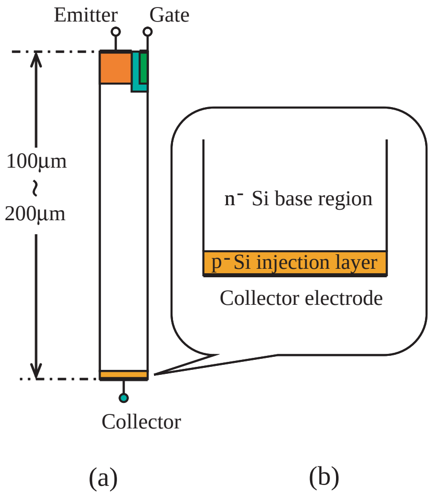

Fig. 1 Schematic cross-sectional view of thin-wafer IGBT.

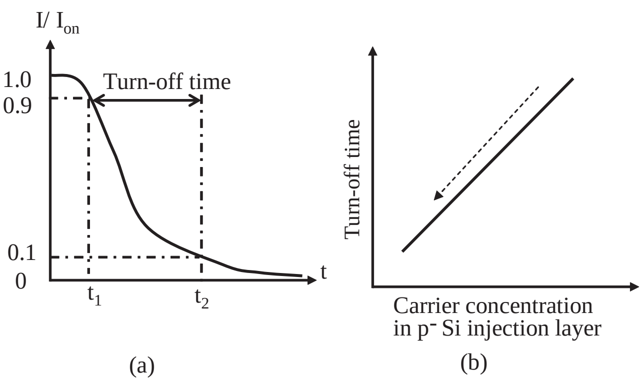

Fig. 2 (a) Schematic turn-off curve
(b) Turn-off time vs carrier concentration in p^- Si injection layer.

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Figure 3 shows the calculated contact resistances for p-type Si-Al and p-type Ge-Al systems, as a function of carrier concentration. The values of barrier height for p-type Si-Al and p-type Ge-Al are 0.35eV and 0.25eV, respectively.[6] For p-type Si with lower carrier concentrations from 10^{16}cm^{-3} to 10^{17}cm^{-3}, the contact resistances are in the order of $10^{-3}\Omega$ -cm^2, resulting in a voltage drop of 0.2V at a current density of 200A/cm^2. This voltage drop is not negligible if on-voltage is about 2V. On the other hand, using p-type Ge as a contact layer is expected to make allow low-resistivity contact because of its narrow energy band gap, as mentioned above.

3. Novel device structure

3. 1 Collector structure and energy band diagram

Figure 4 shows schematic cross-sectional views of two types of collector structures investigated in this study. Figure 4(a) is our proposed structure, which has a p$^+$ Ge contact layer on a conventional p$^-$ Si injection layer. Figure 4(b) is a structure where a p$^+$ Si contact layer is added on a conventional p$^-$ Si injection layer to make a low-resistivity contact. This structure has been recently reported by Tanaka et al.[7] In this paper, our proposed structure and the previously reported one are called Type I and Type II, respectively. For comparison between the two types, the ideal energy band diagrams of the two collector structures are schematically shown in **Fig. 5**. In Type II, the hole-injection from a p-type collector to a n-type base will increase with the carrier (hole) concentration in the p$^+$ Si contact layer. In Type I, the hetero-junction between Si and Ge has hole and electron band offsets at the interface as shown in Fig. 5(a). The hole band offset (ΔE_V) is expected to suppress the hole-injection, even if the carrier concentration increases. Also, the electron band offset (ΔE_C) is expected to maintain good electron transparency because of the lack of the barrier height at the interface. Consequently, we chose Ge as the contact material with the p$^-$ Si injection layer of the thin-wafer IGBTs.

3. 2 Simulation results of turn-off time and on-voltage

Figure 6 shows the simulated values of turn-off time and on-voltage for the two devices as a function of the carrier concentrations in the contact layers. The turn-off time and on-voltage of Type II respectively become longer and lower with increasing carrier concentration in the p$^+$ contact layer. The turn-off time and the on-voltage of Type

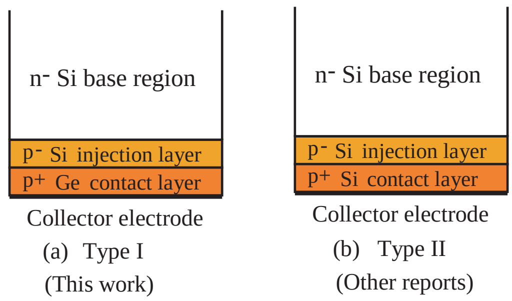

Fig. 4 Schematic cross-sectional views of two collector structures (Type I and Type II).

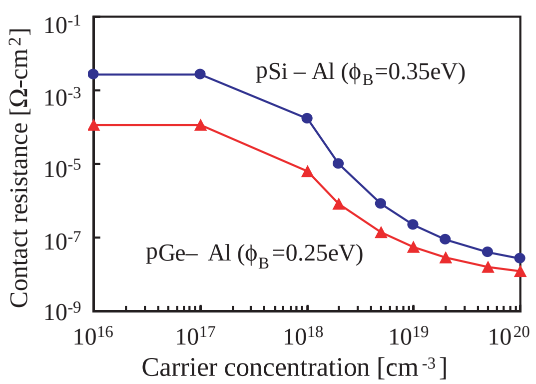

Fig. 3 Calculated contact resistance for p-type Si-Al and p-type Ge-Al systems as a function of carrier concentration.

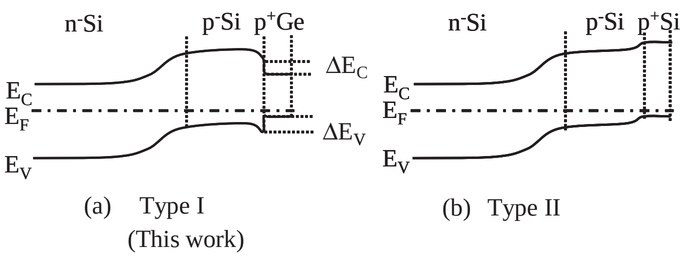

Fig. 5 Schematic energy band diagrams for two types of collector structures.

I, on the other hand, are independent of the carrier concentration in the p^+ contact layer. This indicates that the p^+ Ge contact layer suppresses hole-injection from the p^+ contact layer to the n^- base region.

4. Experimental results and discussion

4. 1 Fabrication

To fabricate the new collector structure, a Ge layer was deposited on a p^- Si injection layer by Electron Beam evaporation. After high dose boron implantation into the Ge layer, laser annealing for improving the crystallization was performed to make the implanted boron ions highly active. The crystallization of the Ge layer after the laser annealing was examined by X-ray Diffraction. Laser annealing was also performed to obtain the p^+ Si contact layer of Type II.

4. 2 Device characteristics and contact resistance

To verify the simulation results, thin-wafer 1.2kV-200A NPT-IGBTs with different collector structures (Type I, Type II and conventional) were fabricated. Several samples were fabricated for each type device, and their turn-off time and on-voltage were measured. **Figure 7** shows the turn-off curves of Type I and Type II. Predictably, the turn-off time of Type II is longer than that of Type I. This clearly indicates that an increase of hole-injection as in Type II largely determines turn-off time. Moreover, **Fig. 8** shows the relationship between turn-off times and on-voltages for the three devices. The turn-off times of type I are almost the same as those of the conventional devices, and shorter than those of type II. This indicates that an increase of hole-injection can be suppressed, in spite of the high carrier concentration in contact layer. The on-voltages of type I are slightly lower than those of the conventional devices. The lower on-voltages of Type I probably are due to the low contact resistances caused by the high carrier concentration in the collector. Thus, we measured the contact resistances and the carrier concentrations in the collectors for the three types of devices.

The contact resistance was measured by the Kelvin probe method, and the carrier concentration was determined by Hall measurement. **Figure 9** shows the contact resistances and the carrier concentrations. The contact resistances of Type I and Type II are lower than those of the conventional device. It appears that the high carrier concentrations of type I

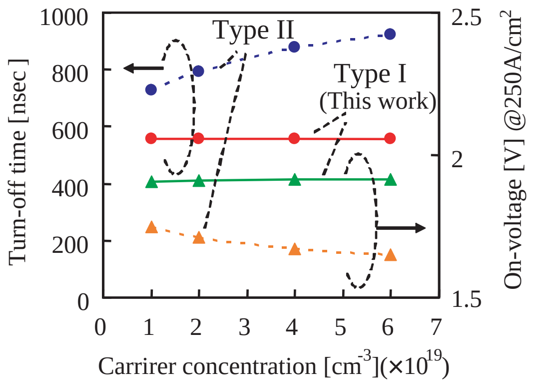

Fig. 6 Simulated turn-off times and on-voltages for two types (Type I and Type II) as a function of carrier concentrations in contact layers.

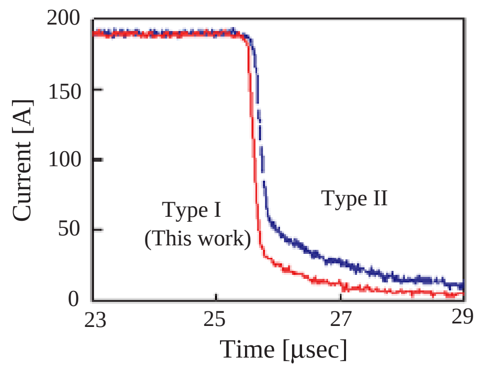

Fig. 7 Turn-off curves of two types (Type I and Type II).

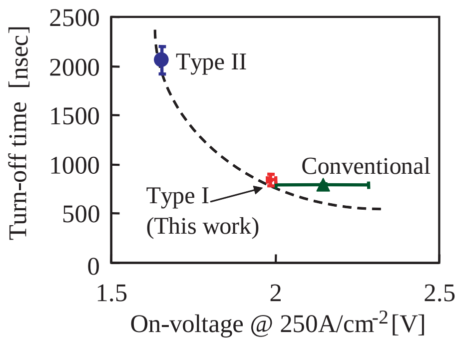

Fig. 8 Relationship between turn-off time and on-voltage for three types of devices.

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and Type II resulted in the lower contact resistances. Conversely, the low carrier concentrations of the conventional device caused the high contact resistances, resulting in the higher on-voltages. The mean value of the contact resistances of the conventional device is about $1\times 10^{-3}\Omega\text{-cm}^2$. The voltage drop arising from the contact resistance is estimated to be 0.25 volts at a current density of 250A/cm^2, agreeing with the on-voltage deviation shown in Fig. 8. The estimated voltage drop for type I is lower than that of the conventional device, even if the maximum value of the contact resistance is posited for the latter. Therefore, our proposed device provides small on-voltage because of its low-resistivity contact, and thus has some advantages for mass production.

5. Conclusion

We proposed a novel collector structure for thin-wafer IGBTs. The collector structure has a p^+ Ge contact layer on the p^- Si injection layer. Simulations and experimental results indicated that a thin-wafer IGBT with this collector structure had low-resistivity contact without an increase in turn-off loss.

Acknowledgements

The authors would like to thank all the members of the electronics engineering div. III in Toyota Motor Corp. for their encouragement and support with IGBT fabrication.

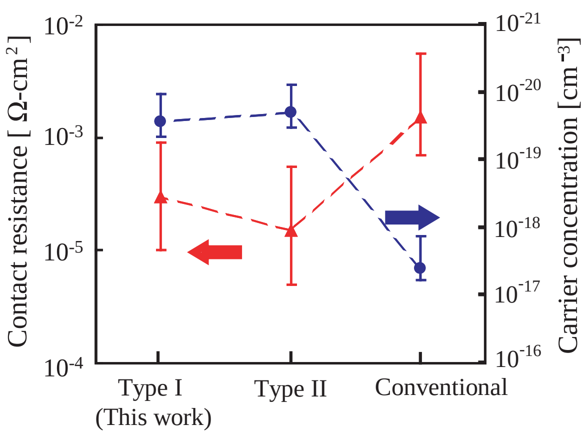

Fig. 9 Measured contact resistances and carrier concentrations in collector for three types of devices.

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(Report received on Sept. 17, 2004)

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