特集 Electrical Properties of Super Junction p-n Diodes Fabricated by Trench Filling*

山内庄一 服部佳晋 山口 仁
Shoichi YAMAUCHI Yoshiyuki HATTORI Hitoshi YAMAGUCHI

We have fabricated Super Junction (SJ) p-n diodes by our previously proposed defect-less trench filling technique with pre- and post-annealing in H2. The trench filling technique has been applied to a comparatively low aspect ratio p/n column structure. Electrical measurements of the SJ p-n diode indicate an increase in breakdown voltage from 70V to 195V due to the multi RESURF effect of the p/n column structure. The leakage current of the diode is below $1x10^{-7}A/cm^2$ at a reverse bias voltage of 150V. It has been experimentally confirmed that complete depletion occurs when the number of acceptors in the p column is equal to that of donors in the n column.

Key words : Super Junction p-n diodes, Multi RESURF effect, Trench filling

1. INTRODUCTION

New conceptual power MOSFETs which utilize "Super Junction (SJ)" or "multi RESURF effect", have been proposed to improve a trade-off relationship between breakdown voltage and specific on-resistance.[1] These types of MOSFETs need a high aspect ratio p/n column structure. Several techniques such as buried multi-epitaxial growth,[1] Super Trench Power MOSFET process,[2] Vapor Phase Doping[3] and trench filling epitaxial Si growth,[4)~6)] have been applied to formation of the high aspect ratio p/n column structures. Among them, the trench filling technique is most simple and suitable for making high aspect ratio p/n column structures, because the carrier concentration uniformity and the integration density of the technique are higher than those of any other proposed techniques.[1)~3)]

Recently, we proposed a new process for trench filling epitaxial Si growth with the following three distinguishing features:[4) 5)]

(1) Pre-annealing in H_2 prior to the filling epitaxial growth is effective in the defect-less trench filling.

(2) Epitaxial growth with HCl etching is valid for preventing voids generation. The HCl etching is optionally performed for the formation of the high aspect ratio structure.

(3) Post-annealing in H_2 after the filling epitaxial growth reduces crystal defects and micro voids in the filled epitaxial layer due to surface migration effect of Si atoms.

In this study, we have fabricated SJ p-n diodes using the above techniques for a comparatively low aspect ratio p/n column structure (aspect ratio: 3.3). The breakdown voltage of diodes expected from the multi RESURF effect has been successfully obtained. A relationship between the breakdown voltage and charge balance conditions of p and n columns width and dopant concentration has been confirmed by the experimental results.

2. EXPERIMENTAL

The fabrication process of the SJ p-n diode is shown in **Fig. 1**. First, trenches of width 3.0μm and depth 10μm (aspect ratio: 3.3) were formed on an n-type (phosphorus doped) Si(110) wafer by anisotropic alkali etching (**Fig. 1**(b)). After the removal of a native oxide layer using an HF solution, the wafer was loaded into a low-pressure chemical vapor deposition (LP-CVD) chamber. Then, a p-type (boron doped) layer was epitaxially grown on the wafer surface to fill the trenches using the method previously proposed[5] (**Fig. 1**(c)). The key steps of the epitaxial process were as follows: (A) pre-annealing with H_2 gas flow (>1000°C), (B) low-temperature epitaxial growth (<1000°C), (C) post-annealing with H_2 gas flow (>1000°C). The above steps (A)-(C) were sequentially performed using a rapid thermal annealing system in the LP-CVD chamber with a pressure of 10^4 Pa. After the formation of a p+ diffused region on the surface of

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the p/n column structure, a metal layer was finally deposited to make electrical contacts to the devices (**Fig. 1**(d)).

The structural parameters of the p/n column are shown in **Fig. 1**(c). W_p and W_n are initial p column and n column widths, which correspond to those of the pillar and the trench, respectively. Np and Nn are the dopant concentrations of boron in the p column and phosphorus in the n column, respectively. Both dopant concentrations of the p/n column were measured by Secondary Ion Mass Spectroscopy (SIMS). The above parameters were experimentally determined to obtain the charge balance of the p/n column structure.

The cross-sectional doping image of the fabricated SJ p-n diode was observed by Scanning Capacitance Microscopy (SCM), which directly demonstrates carrier concentration image of the sample.

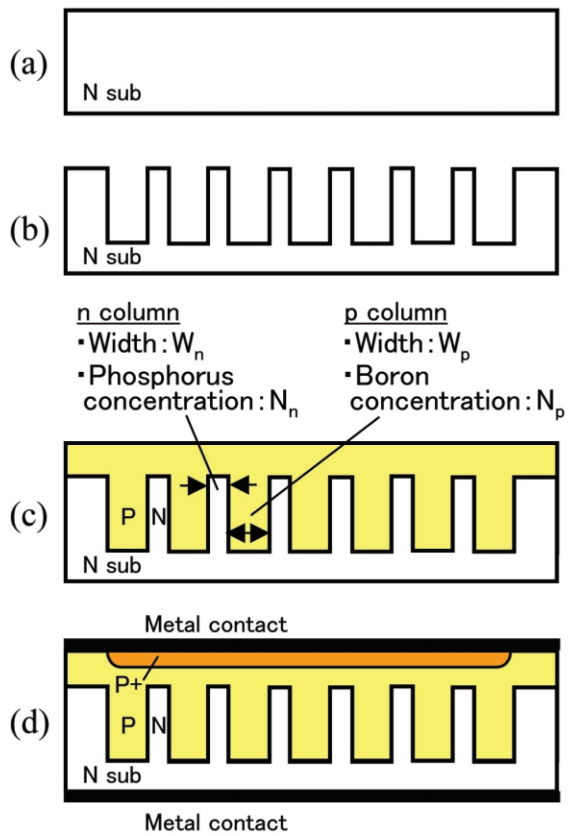

Fig. 1 Schematic process flow of SJ p-n diode

3. RESULT AND DISCUSSION

Figure 2 shows a cross-sectional SCM image of a typical SJ p-n diode (p/n column depth:9.5 µm, Wp:3 µm, Wn:1 µm, Np: $\sim 10^{15}/cm^3$, Nn: $\sim 10^{16}/cm^3$). The SCM image clearly shows a p/n column structure and a micro-void in each of the p columns. The bottom shape of each p column is round. Our previous study has shown that such a round shape is due to surface migration of Si atoms on the inner wall of trenches, which is caused by pre-annealing in H2 step[5].

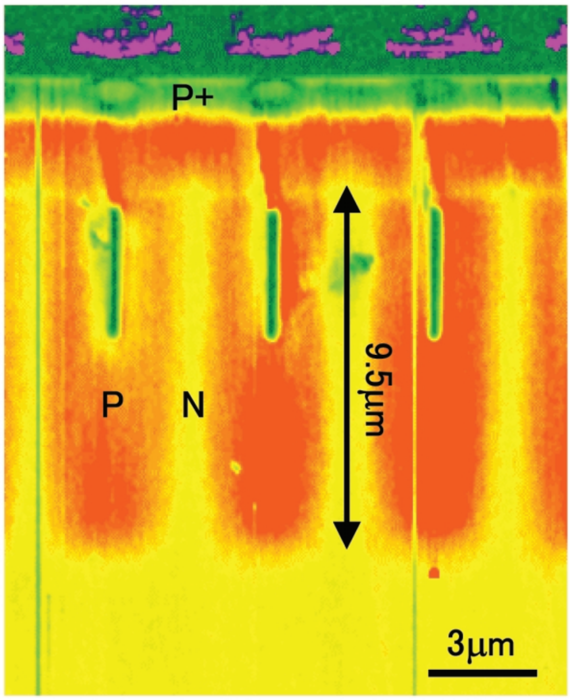

Fig. 2 Cross-sectional SCM image of typical SJ p-n diode

Figure 3(a) and (b) show the reverse and forward biased I-V characteristics of the SJ p-n diode, respectively. Both characteristics are compared with those of a single-trench p-n diode formed on the same Si wafer. The schematic structures of the two diodes are also shown in **Fig. 3**.

In **Fig. 3**(a), an increase in breakdown voltage from 70V to 195V clearly shows the multi RESURF effect of the p/n column structure of the SJ diode. The breakdown voltage of 195V for the SJ diode is in good agreement with the value simulated for a p/n column depth of 9.5µm. Thus, the influence of the micro-voids on breakdown voltage is small as estimated in our previous work [4]. The leakage current of the SJ diode is below $1x10^{-7}A/cm^2$ at a reverse bias voltage of 150V. Such a property indicates good crystallographic quality of p-n junction of the SJ diode due to the defect-less epitaxial growth with pre- and post-annealing in H_2.[5]

As for the forward biased I-V characteristics in **Fig. 3** (b), the influence of recombination current is small for both diodes, because the ideal factors for both diode are almost consistent with 1. Such a diffusion current dominated property also supports good crystallographic quality of the p-n junction.

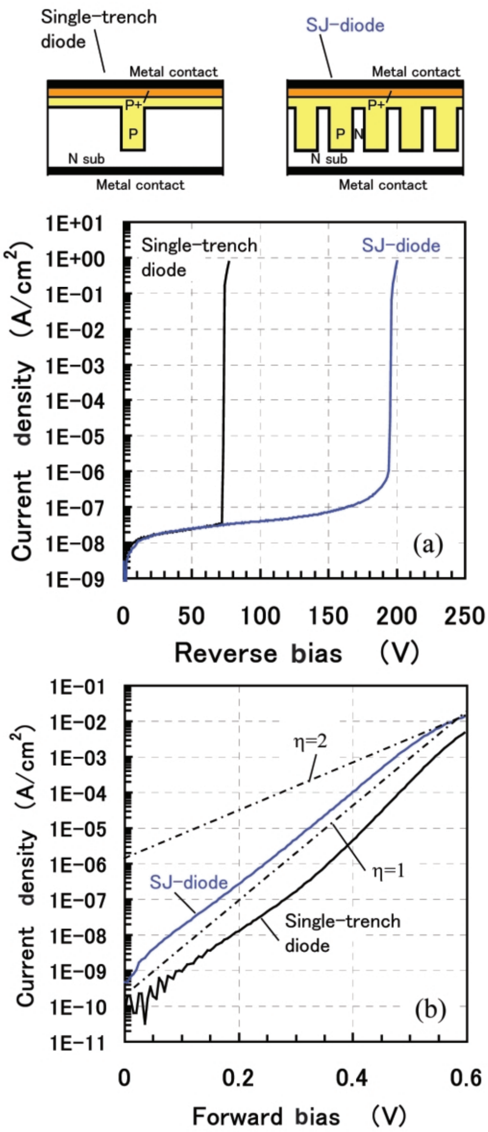

Fig. 3 Reverse (a) and forward (b) I-V characteristics of SJ diode and single-trench diode, respectively The broken lines indicate ideal slopes for ideal factors η of 1 and 2.

Figure 4 shows the relationship between the breakdown voltage and the charge balance conditions. α_p and α_n are normalized values of N_p x W_p and N_n x W_n, respectively. Briefly, α_p and α_n reflect the numbers of acceptors and donors in the p-n column structure, respectively. For α_n=1.0, a maximum breakdown voltage of 195V is obtained around α_p=1.0. For other values of α_n, the same breakdown voltage is obtained when $\alpha_n = \alpha_p$. Hence, it is experimentally confirmed that complete depletion occurs when the number of acceptors in the p column is equal to that of donors in the n column.

The property of the breakdown voltage in **Fig. 4** reflects the sensitivity of the breakdown voltage to carrier imbalance. 20% carrier imbalance causes an about 10% reduction of the breakdown voltage. On the other hand, a study of a high voltage (680V) SJ-MOSFET fabricated by a buried multi epitaxial technique also discussed the influence of doping imbalance, which was controlled by implantation and diffusion processes.[7] Its experimental results indicated a 10～25% reduction in breakdown voltage of the device for 8% doping imbalance. The strict comparison between the experimental results of different breakdown voltage and specific on-resistance of the devices might be difficult, but it is necessary to clarify one influence of the carrier concentration uniformity which depends on fabrication technique. For the determination of the SJ fabrication process, future discussions will not only focus on process cost but also process potential such as uniformity and controllability of carrier concentration.

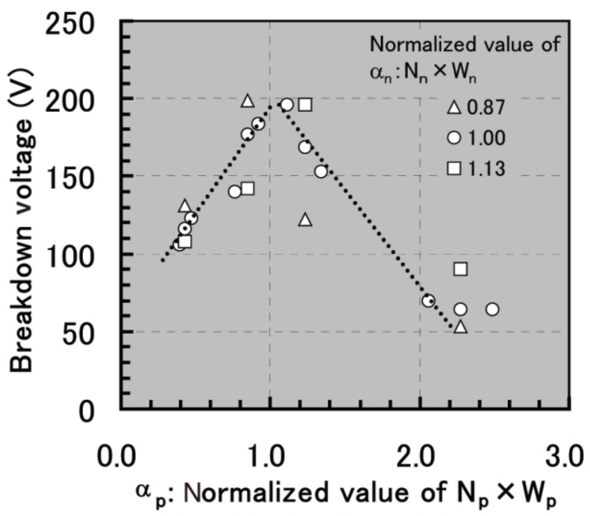

Fig. 4 Breakdown voltages as a function of α_p and α_n. The dotted line indicates the properties for α_n=1.0

4. CONCLUSIONS

We have fabricated SJ p-n diodes by our previously proposed defect-less trench filling technique with pre- and post-annealing in H2. The electrical properties of the SJ p-n diodes have indicated the following:

The increase in breakdown voltage from 70V to 195V clearly shows the multi RESURF effect of the p/n column structure. The leakage current of the SJ diode is below 1x10-7A/cm^2 at a reverse bias voltage of 150V. Such a property indicates a good crystallographic quality of p-n junction. It has been experimentally confirmed that complete depletion occurs when the number of acceptors in the p column is equal to that of donors in the n column.

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＜著　者＞

山内　庄一
（やまうち　しょういち）
基礎研究所
理学博士
車載用半導体プロセス開発に従事

山口　仁
（やまぐち　ひとし）
基礎研究所
車載用半導体デバイス開発に従事

服部　佳晋
（はっとり　よしゆき）
（株）豊田中央研究所
半導体デバイス・センサ研究室
工学博士
車載用半導体デバイス開発に従事