A Low Knee Voltage of 4H-SiC TSBS Employing Poly-Si/Ni Dual Schottky Contacts

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Abstract

We report a low knee voltage and high breakdown voltage 4H-SiC TSBS employing poly-Si/Ni dual Schottky contacts. A knee voltage was improved from 0.75 to 0.48 V by utilizing alternative low work-function material of poly-Si as an anode electrode. Also, reverse breakdown voltage was improved from 901 V to 1,154 V. SiC TSBS with poly-Si/Ni dual Schottky scheme is a suitable structure for high-efficiency rectification and high-temperature operation.

INTRODUCTION

Since 4H-SiC SBD provide a low forward voltage drop and a fast switching speed due to wide bandgap properties and short reverse recovery time, SiC SBD has an attention for next-generation power semiconductor device.

However, ordinary SiC SBD with single Schottky contact without any trench structure exhibits a considerable trade-off relationship between a forward voltage drop and reverse blocking characteristics. Therefore, a new design is required to break through the trade-off relationship of SiC SBD.

For design of TSBS, two different work-function electrodes are typically used as anode. Under small positive potential condition, the current conduction occurs through a low work-function anode so that low knee voltage is available. For positive potential, larger than high work-function material, forward current flows through entire regions of SiC TSBS. Under reverse bias, expanded depletion region from the high work-function electrode formed on trench shields the low work-function anode on unetched regions so that reverse leakage current is effectively suppressed [1-3].

Ti and Ni are widely used for Schottky contacts of 4H-SiC TSBS [1]. This Ti/Ni metal scheme induces thermal instability and relatively complicated photo-lithography procedure with a consideration of align-margin between Ti and unetched regions.

In this paper, we propose self-align process between trench etching and formation of the low work-function electrode to reduce a width of unetched mesa and improve the reverse breakdown voltage. Poly-Si was employed for low work-function electrode to achieve a low knee voltage.

Poly-Si has many merits when used as an anode. Poly-Si is possible to be deposited through CVD at high temperature (700 ℃) so that it provides thermal stability. Also, relatively high-temperature PDA is available for enhance of Schottky characteristics. In addition, poly-Si etching would be carried out with no metal contamination and high etching selectivity to SiC than metal/SiC stack. Moreover, the most attractive advantage of poly-Si is lower work-function than Ti, so we utilize poly-Si as the anode material of TSBS to improve forward characteristics.

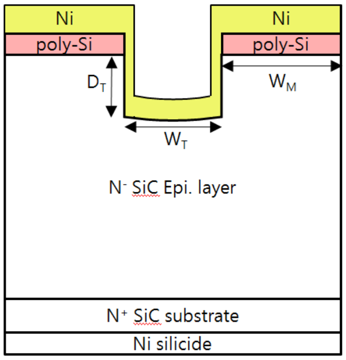


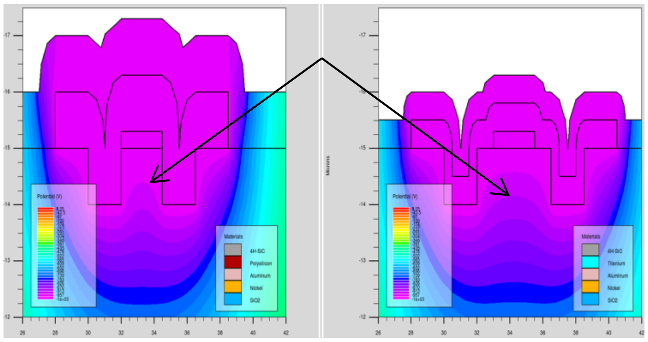
Fig. 1. A cross sectional view of the proposed SiC TSBS with poly-Si/Ni dual Schottky electrodes. W_M (2, 2.5 and 3 μm), W_T (4 μm) and D_T (1 μm) are mesa width, trench width and trench depth, respectively.

DEVICE DESIGN AND FABRICATION

A cross sectional view of the proposed SiC TSBS with poly-Si and Ni anodes is shown in Fig. 1. A 15 μm-thick n-type 4H-SiC epitaxial layer with doping concentration of 1×10^{15} cm^{-3} is used for fabrication of SiC TSBS. As the first procedure, a 300 nm-thick poly-Si anode (n-type) and 2 μm-thick SiO_2 etch mask were formed on the SiC epi layer by LPCVD and PECVD, respectively.

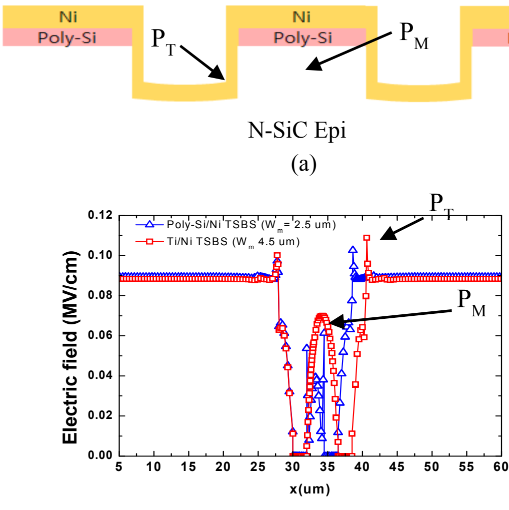
The poly-Si pattern was formed by etching SiO_2 mask and poly-Si in sequence by ICP-RIE. These two layers are served as a self-align etch mask for formation of trench structure. Then, 100 nm-thick Ni was sputtered on back-side and annealed at 950 ℃ for 90 s in RTA system for ohmic contact. After removing front-side SiO_2 etch mask, 200 nm-thick Ni was formed on entire regions including trench and top of poly-Si by sputtering. Finally, the samples were annealed at 300 ℃ for 10 min under N_2 ambient to improve SBH and uniformity of the barrier.

A Ti/Ni TSBS and SBDs without trench structure, which use poly-Si, Ti and Ni, were also fabricated for comparison analysis. The Ti/Ni TSBS include 1 µm-width align margin between Ti and the unetched mesa. The two-type of devices, Ti/Ni TSBS and poly-Si/Ni TSBS have identical cell-pitch. In case of mesa, the width was varied from 2 to 3 µm for poly-Si/Ni device, however, the width of mesa for Ti/Ni one was 4 to 5 µm results from align margin. The trench depth was fixed to 1 µm for all devices.



(a) (b)

Fig. 2. Potential of (a) poly-Si/Ni TSBS (W_m= 2.5 µm) and (b) Ti/Ni TSBS (W_m=4.5 µm) at –1,000 V.



(a)

(b)

Fig. 3. (a) poly-Si/Ni TSBS structure (b) electric field distribution of poly-Si/Ni TSBS (W_m= 2.5 µm) and Ti/Ni TSBS (W_m= 4.5 µm) at –20 V.

SIMULATION

Silvaco TCAD simulations have been used to verify the potential and electric field distribution in SiC TSBS. We confirmed that potential of poly-Si/Ni TSBS (W_m= 2.5 µm) is larger than potential of Ti/Ni TSBS (W_m= 4.5 µm) in Fig. 2 at the arrow point. Also, the structure of simulated poly-Si/Ni TSBS, Ti/Ni TSBS and electric field are shown in Fig. 3 (b). Simulation shows that as the mesa width decreases, the electric field decreases in the P_T and P_M of Fig. 3 (a). As the mesa width narrowed, the electric field at P_M and P_T is reduced by the more effective shielding effect. As a result, we have improved the reverse breakdown voltage from 1,444 V to 1,473 V by 102 V through poly-Si/Ni TSBS in simulation.

In addition, the simulation results in Fig. 5 show that TSBS has low knee voltage by using poly-Si anode instead of Ti anode. Although mesa width of poly-Si/Ni TSBS is narrower than mesa width of Ti/Ni TSBS, current of poly-Si/Ni TSBS is higher under 0.5 V in the simulation results of Fig. 5. However, since the size of poly-Si/Ni TSBS is smaller by 2 µm than Ti/Ni TSBS, forward current of Ti/Ni TSBS has higher current at above knee voltage as shown in Fig. 5 above about 0.5 V. Extra space of 2 µm is required to obtain identical length of Ti anode with poly-Si one without self-align process.

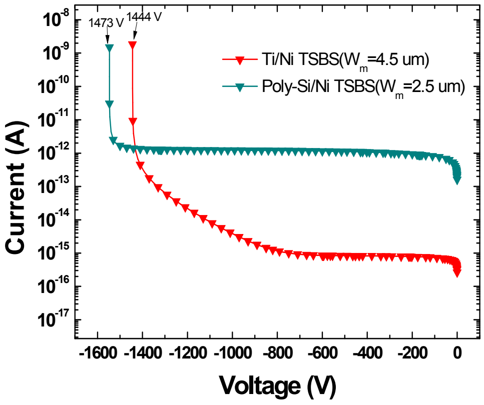


Fig. 4. Reverse I-V characteristics of the simulation in log-scale.

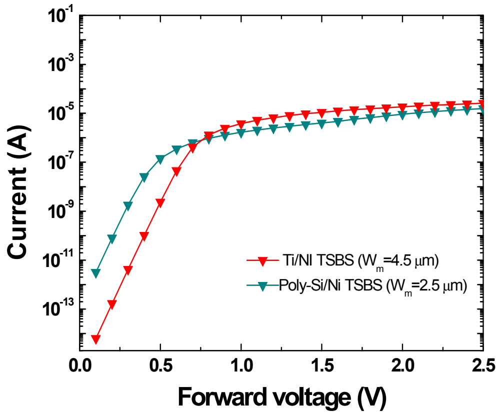


Fig. 5. Forward I-V characteristics of the simulation in log-scale.

RESULTS

The forward I-V characteristics of the poly-Si/Ni TSBS, the Ti/Ni TSBS and SBDs without trench are shown in Fig. 6. The ideality factor (n) and Schottky barrier height (Φ_b) were extracted with a current-voltage measurement [2, 4]. According to the thermionic emission theory [2, 5], the current density J= I/V can be approximated as:

$$J = A^{**}T^2 e^{\frac{-q\Phi b}{kT}} e^{\frac{qV}{nkT}} \qquad (1)$$

with the assumption that the applied voltage V is much larger than kT/q where, A^{**} is the effective Richardson's constant, A is the device area, k is the Boltzmann's constant, q is the electron charge, and T is the absolute temperature [2, 5]. We obtained slope in linear region of forward I-V graph to calculate the n and SBH. For the evaluation of n and Φ_b, the theoretical values of the effective Richardson constant were used (146 A cm^{-2} K^{-2} for 4H-SiC [2, 6]).

TABLE I

IDEALITY FACTOR (N), SCHOTTKY BARRIER HEIGHT (Φ_B) AND FORWARD VOLTAGE DROP.

	n	**Φ_b (eV)**	**Forward voltage drop**
Pure poly-Si	1.03	0.86	1.44 V
Pure Ti	1.11	1.08	1.68 V
Pure Ni	1.09	1.50	2.04 V
Ti/Ni TSBS	1.06	1.13	1.86 V
poly-Si/Ni TSBS	1.05	0.96	1.84 V

The extracted SBH values of Ti/Ni TSBS and poly-Si are 1.13 and 0.96 eV, respectively. The lower theoretical work function value of poly-Si (Φ_{Si}= 4.05 eV) than that of Ti (Φ_{Ti}= 4.33 eV) agrees well with the SBH values. Due to the low SBH of poly-Si/Ni TSBS, the low knee voltage of 0.48 V is achieved at 3 µA, while that of Ti/Ni TSBS is 0.75 V. Meanwhile, the ideality factors of TSBS devices are almost identical ($n_{Ti/Ni}$= 1.06, $n_{poly-Si/Ti}$= 1.05). Ni SBD has a rather high knee voltage of 1.5 V owing to high work-function of 5.15 eV for Ni [4].

Poly-Si/Ni TSBS and Ti/Ni one show a similar forward voltage drop values of 1.84 and 1.86 V at 100 A/cm^2 due to the different trench width ($W_{T,poly-Si/Ni}$= 4 µm, $W_{T,Ti/Ni}$= 2 µm).

In case of Ti/Ni TSBS, it has similar forward characteristics to Ti SBD, but poly-Si/Ni has difference from poly-Si SBD unlike Ti/Ni TSBS. Because mesa width of poly-Si/Ni TSBS is narrower than mesa width of Ti/Ni TSBS, it has shielding effect under zero bias.

Fig. 7 shows reverse characteristics of poly-Si/Ni TSBS, Ti/Ni TSBS and various SBDs. Reverse breakdown voltage of poly-Si/Ni TSBS (1,153 V) with W_M= 2 µm is higher than that of Ti/Ni TSBS (901 V) with W_M= 4 µm. Although poly-Si SBD has low breakdown voltage to low Schottky barrier height under low reverse voltage, using poly-Si/Ni TSBS was improved reverse breakdown voltage to poly-Si, Ti SBD and Ti/Ni TSBS. A low work-function anode is effectively shielded by Ni electrode on trench structure due to narrow mesa width by the self-align process in poly-Si/Ni TSBS. The breakdown voltage of poly-Si/Ni TSBS decreases with increment in mesa width. Our experimental results shows the identical tendency as simulation one.

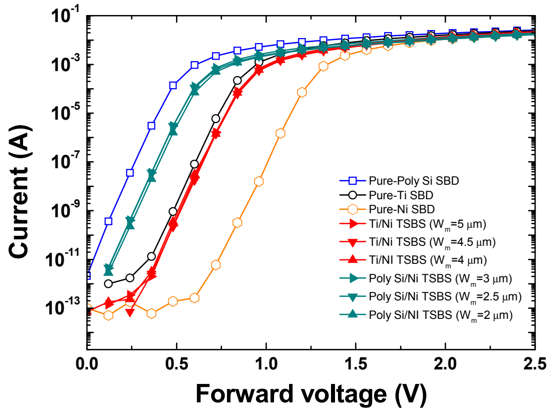


Fig. 6. Forward I-V characteristics of the fabricated TSBS and SBDs in log-scale.

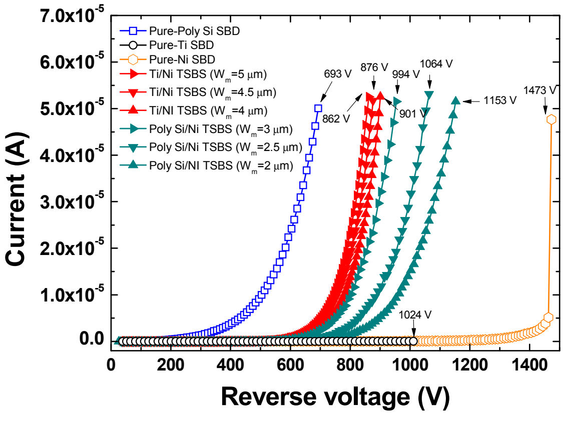


Fig. 7. Reverse I-V characteristics of the fabricated TSBS and SBDs.

However, the breakdown voltage of Ti/Ni TSBS devices are lower than that of Ti SBDs as well as they show a weak dependency on mesa width, meaning that the wide mesa width causes itself not be shielded by depletion from Ni. As we have demonstrated in previous simulations, the wider the mesa width has, the smaller the potential has and the larger the electric field is concentrated in the trench edge (P_T in Fig. 3 (a)), resulting premature reverse breakdown.

CONCLUSIONS

A low-knee-voltage SiC TSBS utilizing poly-Si/Ni dual Schottky contacts and the self-align process was proposed and demonstrated. A considerably low knee voltage of 0.48 V was achieved by employing poly-Si anode for TSBS, while that of conventional Ti/Ni TSBS was 0.75 V. The reverse breakdown voltage is also improved due to shrunk mesa width so that the low work-function anode is effectively shielded by depletion. The breakdown voltage of the proposed poly-Si/Ni TSBS was 1,153 V, however, the conventional Ti/Ni TSBS shows 901 V only. Consequently, the dual Schottky contacts including poly-Si and Ni are promising and suitable for high-efficiency and high-performance SiC power diodes.

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ACRONYMS

SBD: Schottky Barrier Diode
TSBS: Trench Schottky Barrier controlled Schottky diode
PDA: Post deposition annealing
D_T: Trench depth
W_M: Mesa width
W_T: Trench width
LPCVD: Low Pressure Chemical Vapor Deposition
PECVD: Plasma-Enhanced Chemical Vapor Deposition
ICP-RIE: Inductively Coupled Plasma Reactive Ion Etching
P_T: Trench edge point
P_M: Mesa width point
SBH: Schottky Barrier Height
RTA: Rapid Thermal Annealing