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1330 V, 67 mΩ · cm² 4H-SiC(0001) RESURF MOSFET

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Abstract—Design and fabrication of 4H-SiC(0001) lateral MOSFETs with a two-zone reduced surface field structure have been investigated. The dose dependencies of experimental breakdown voltage show good agreement with simulation. Through the optimization of implant dose, high-temperature (1700 °C) annealing after ion implantation, and reduction of channel length, a breakdown voltage of 1330 V and a low on-resistance of 67 mΩ · cm² have been obtained. The figure-of-merit (V_BR/ID) of the present device reaches 26 MW/cm², being the best performance among lateral MOSFETs reported. The temperature dependence of static characteristics is also presented.

Index Terms—Power device, power MOSFET, reduced surface field (RESURF), silicon carbide (SiC).

Owing to the high critical electric field, silicon carbide (SiC) is a promising wide bandgap semiconductor for high-voltage power device applications [1]. Recent improvement in channel mobility of MOS devices has resulted in demonstration of vertical SiC MOSFETs which significantly outperform the Si counterparts [2]–[6]. Although lateral SiC power MOSFETs are more suited for future power IC applications, the performance of lateral SiC MOSFETs has still suffered from high on-resistance and relatively low breakdown voltage, compared to vertical SiC MOSFETs [7]–[10]. In this letter, simulation and fabrication of high-voltage SiC reduced surface field (RESURF) MOSFETs are investigated, leading to a record performance. The temperature dependence of static characteristics is also discussed.

Fig. 1 illustrates the schematic structure of a RESURF MOSFET fabricated in this letter. The structure is basically the same as the “two-zone” RESURF MOSFET [7]. Both the RESURF and lightly doped drain (LDD) regions were 10 μm long and 0.6 μm deep. RESURF/MOSFETs were fabricated on 10 μm-thick p-type 8° off axis 4H-SiC(0001) epilayers doped to 7 × 10¹⁵ cm⁻³. The RESURF/LDD regions were formed by N⁺ implantation at room temperature, while high-dose (4 × 10¹⁵ cm⁻²) P⁺ implantation at 300 °C was employed to form source/drain. The P⁺-contact region was formed by Al⁺ implantation. Post-implantation annealing was performed at 1700 °C for 20 min in Ar with a carbon cap to suppress surface roughening [11]. After RCA cleaning, 70 nm-thick gate oxides were formed by direct oxidation in N₂O at 1300 °C [12], [13]. The contact metal was Ti/Al annealed at 600 °C for source/drain and Al for gate. The typical channel length and width were 2 μm and 200 μm, respectively.

The RESURF and LDD doses were optimized to reduce the electric field crowding at the drain edge and in the gate oxide by using device simulation (ISE-DESSIS). The breakdown of devices (avalanche in SiC) was defined when the impact-ionization integral along an electric-force line reaches unity. The maximum electric field of oxide at the gate edge was also monitored.

Fig. 2 plots the LDD-dose dependencies of experimental and simulated breakdown voltages of 4H-SiC MOSFETs with a fixed RESURF dose of 2.4 × 10¹² cm⁻². The influence of MOS-interface charge (Qᵣ = −2 × 10¹² cm⁻²) is also simulated.

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the resistance of n+–contact regions including contact resistance. Fig. 4 represents the channel length dependence of on-resistance for 4H-SiC RESURF MOSFETs with various RESURF doses. In Fig. 4, the LDD dose was fixed, while the RESURF dose and channel length were varied. From the slope of the plots, the effective channel mobility could be estimated to be 20–25 cm²/V·s. From the intercept at the ordinate, the sum of $R_{\text{drift}}$ and $R_c$ was determined to be $1240\,\Omega$, 770, and $480\,\Omega$ for a RESURF dose of $6.0 \times 10^{12} \text{cm}^{-2}$, $2.4 \times 10^{12} \text{cm}^{-2}$, and $6.0 \times 10^{12} \text{cm}^{-2}$, respectively. These values are dominated by the resistance of RESURF region, because the RESURF dose is lower than the LDD dose. Since the contact resistance cannot be neglected (about 15–18%) in the present device, further reduction of on-resistance may be achieved by optimizing the annealing process of ohmic contacts.

The temperature dependencies of measured on-resistance and its components are shown in Fig. 5. The MOS-channel resistance showed significant decrease with increasing temperature, because electron trapping at the interface states is less pronounced at elevated temperature. The drift-region resistance becomes high at low temperature because of carrier freezing, and at high temperature due to decrease in bulk mobility. As a result, the total on-resistance of RESURF MOSFET showed a minimum at about room temperature.

Fig. 6 plots the on-resistance versus breakdown voltage for major lateral SiC MOSFETs reported in literature and this work, together with major lateral Si MOSFETs, and $R_c$ the resistance of n+–contact regions including contact resistance.

$$ R_{\text{on}} = \frac{Ld_{\text{ox}}}{\mu_{\text{ch}}w\varepsilon_{\text{ox}}(V_G - V_T)} + R_{\text{drift}} + R_c $$

where $L$ is the channel length, $W$ the channel width, $\mu_{\text{ch}}$ the channel mobility, $d_{\text{ox}}$ the oxide thickness, $\varepsilon_{\text{ox}}$ the dielectric constant of gate oxide, $V_G$ the gate voltage, $V_T$ the threshold voltage, $R_{\text{drift}}$ the resistance of drift region (RESURF and LDD regions), and $R_c$ the resistance of n+–contact regions including contact resistance. Fig. 4 represents the channel length dependence of on-resistance for 4H-SiC RESURF MOSFETs with various RESURF doses. In Fig. 4, the LDD dose was fixed, while the RESURF dose and channel length were varied. From the slope of the plots, the effective channel mobility could be estimated to be 20–25 cm²/V·s. From the intercept at the ordinate, the sum of $R_{\text{drift}}$ and $R_c$ was determined to be $1240\,\Omega$, 770, and $480\,\Omega$ for a RESURF dose of $6.0 \times 10^{11} \text{cm}^{-2}$, $2.4 \times 10^{12} \text{cm}^{-2}$, and $6.0 \times 10^{12} \text{cm}^{-2}$, respectively. These values are dominated by the resistance of RESURF region, because the RESURF dose is lower than the LDD dose. Since the contact resistance cannot be neglected (about 15–18%) in the present device, further reduction of on-resistance may be achieved by optimizing the annealing process of ohmic contacts.

The temperature dependencies of measured on-resistance and its components are shown in Fig. 5. The MOS-channel resistance showed significant decrease with increasing temperature, because electron trapping at the interface states is less pronounced at elevated temperature. The drift-region resistance becomes high at low temperature because of carrier freezing, and at high temperature due to decrease in bulk mobility. As a result, the total on-resistance of RESURF MOSFET showed a minimum at about room temperature.

Fig. 6 plots the on-resistance versus breakdown voltage for major lateral SiC MOSFETs reported in literature and this work, together with major lateral Si MOSFETs. A classical limit of Si unipolar devices without super-junction structures is also shown by a dotted curve. The characteristics of the present
device (1330 V, 67 mΩ·cm²) yielded a high figure-of-merit ($V_B^2/R_{on}$) of 26 MW/cm², being the best performance among lateral MOSFETs reported (3–10 MW/cm²) [7]–[10]. The optimization of LDD dose, high-temperature (1700°C) annealing after ion implantation, and reduction of channel length were key issues to improve the performance.

In summary, the dose optimization and fabrication of 4H-SiC(0001) lateral MOSFETs with a two-zone RESURF structure have been investigated. The dose dependencies of experimental breakdown voltage showed good agreement with simulation. A breakdown voltage of 1330 V and a low on-resistance of 67 mΩ·cm² have been obtained. In this particular device, the contribution of MOS-channel resistance to the total on-resistance was approximately 40%.

REFERENCES


