An Analytical Delayed-Turn-Off Model for 6H-SiC Buried-Channel NMOS Devices Considering Incomplete Ionization

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Abstract

This paper reports an analytical delayed-turn-off model for 6H-SiC buried-channel NMOS devices considering incomplete ionization. As verified by the PISCES results, the analytical model provides an accurate prediction of the IV characteristics of a 6H-SiC buried-channel NMOS device. According to the analytical model, the slope of delayed-turn-off region becomes smaller as the doping density of the buried channel increases.

Summary

The 6H-SiC is receiving a lot of attention for high-temperature and high-power applications owing to its large bandgap, high thermal conductivity, and high breakdown voltage [1]. Using 6H-SiC, buried-channel NMOS devices have been fabricated [2]. Due to a large effective acceptor/donor ionization energy, incomplete ionization of dopants [3] complicates the analysis of SiC MOS devices. In this paper, an analytical delayed-turn-off model for 6H-SiC buried-channel NMOS devices considering incomplete ionization is reported.

As shown in Fig. 1, the 6H-SiC buried-channel NMOS device [2] has a gate oxide of 736 Å and a 0.16 μm n-type buried channel doped with a density of $4.9 \times 10^{17} \text{ cm}^{-3}$ above the p-type 10^{16} cm^{-3} substrate. In order to facilitate 2D analysis for the 6H-SiC NMOS device, PISCES simulation has been used with appropriate parameters including bandgap, densities of states, and mobilities. In addition, the ionized impurity concentrations have been modeled using Fermi-Dirac statistics with the effective donor and acceptor ionization energies [4]. Fig. 2 shows the I_D vs. V_G curves of the 6H-SiC buried-channel NMOS device with a channel junction depth of 0.08 μm, 0.16 μm, and 0.32 μm, biased at $V_B = 0 \text{ V}$, -6 V , based on the PISCES results. At $V_G = 5 \text{ V}$, it's in the accumulation region. As shown in the figure, as V_G becomes more negative, it's in the delayed-turn-off region. With a buried channel of 0.32 μm and 0.16 μm, as the drain current reaches a certain negative value, a more negative V_G does not degrade the drain current as a result of surface hole inversion.

In the delayed-turn-off region, the buried-channel is partially depleted. As indicated in Fig. 1, the vertical direction of the device can be divided into three sections. In the channel region, the electric field is negligible, from charge neutrality considering incomplete ionization, one obtains Eq. (1) as shown in Fig. 3. Note that in the channel region, incomplete ionization is important since $E_C - E_D$ is large as shown in Fig. 3. From Eqs. (1)-(3), the channel potential is as Eq. (4). In the partially ionized regions above and below the channel region, the Poisson's equation is as Eq. (5). Solving the Poisson's equation with boundary conditions as Eqs. (6)&(7), the electric field at the boundary is as Eq. (8). Considering the voltage drop across the partially ionized region and from Eq. (8), the width of partially ionized region and the effective charge density have been obtained as Eqs. (9)&(10). In the fully ionized regions above and below the partially ionized regions, the Poisson's equation is Eq. (11). Solving the Poisson's equation with boundary conditions, the widths of the fully ionized regions are as Eqs. (12)-(14). In the delayed-turn-off region, the conduction current is expressed as Eq. (15). At the onset of hole inversion at the oxide interface, the hole density is expressed as Eq. (16). From Eq. (16), the surface potential and consequently the gate voltage have been obtained as Eqs. (17)&(18). As the buried-channel is fully depleted, the gate voltage is as Eq. (19).

Fig. 2 shows the I_D vs. V_G curves of the 6H-SiC buried-channel NMOS device with a channel junction depth of 0.08 μm, 0.16 μm, and 0.32 μm, biased at $V_B = 0 \text{ V}$, -6 V , based on the analytical model and the PISCES results. A good match between the model results and the PISCES data

can be observed. Fig. 5 shows (a) the electron density distribution and (b) electrostatic potential distribution in the substrate direction of the 6H-SiC buried-channel NMOS device biased at $V_G = +5V$ (accumulation), $-10V$ (delayed-turn-off), $-20V$ (inversion) based on the analytical model and the PISCES results. As indicated in the figure, incomplete ionization of donors in the channel region can be seen. A good match between the model results and the PISCES data can be seen. Fig. 6 shows the transconductance vs. channel doping density curves of the 6H-SiC buried-channel NMOS device biased in the delayed-turn-on region. With a more heavily doped buried channel, the transconductance in the delayed-turn-off region is smaller as a result of the incomplete ionization effect and the concentration-dependent effect. Fig. 7 shows the gate voltage when punchthrough of the buried channel occurs (V_{Gpt}) and the gate voltage when surface inversion starts to happen (V_{Gsi}) vs. the channel doping density of the 6H-SiC buried-channel NMOS device with a channel junction depth of $0.08\mu m$ and $0.16\mu m$, biased at $V_B = 0V$ and $-6V$. For a deeper buried channel of $0.16\mu m$, surface inversion occurs at a less negative V_G since $V_{Gsi} > V_{Gpt}$. Once the surface inversion happens, the device cannot be turned off. Therefore, in order to have a 6H-SiC buried-channel MOS device, which can be turned off, the buried channel should be properly designed such that $V_{Gpt} > V_{Gsi}$.

References

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Fig. 1. Cross section of the 6H-SiC buried-channel NMOS device.

Fig. 2. The I_D vs. V_G curves of the 6H-SiC buried-channel NMOS device with a channel junction depth of $0.08\mu m$, $0.16\mu m$, and $0.32\mu m$, biased at $V_B = 0V$, $-6V$, based on the analytical model and the PISCES results.

Fig. 4. Energy band of the 6H-SiC material.

Figure 1 is a graph showing the temperature dependence of the growth rate G_m (in units of $\times 10^{-9} \text{ ÅV}\mu\text{m}$) versus the donor concentration N_D (in units of $\times 10^{17} \text{ cm}^{-3}$). The y-axis ranges from 0.6 to 1.8, and the x-axis ranges from 2 to 8. Two data series are plotted: PISCES (open circles) and Model (dashed line). The PISCES data points are approximately (3.2, 1.75), (4.2, 1.65), (4.8, 1.55), (5.2, 1.5), (6.2, 1.45), (7.2, 1.35). The Model curve starts at (2, 1.35) and ends at (8, 0.75). Two vertical dashed lines indicate transition temperatures: $T_{tr} = 368 \text{ Å}$ at $N_D \approx 4.2$ and $T_{tr} = 756 \text{ Å}$ at $N_D \approx 4.8$.

Figure 1 consists of two vertically stacked plots sharing a common x-axis representing position X in μm , ranging from 0 to 0.8.

The top plot shows Electron Concentration in cm^{-3} on a logarithmic y-axis from 10^0 to 10^8 . It displays three curves for different gate voltages V_g : $+5\text{V}$, -10V , and -20V . The $+5\text{V}$ curve is a solid line with a plateau at 10^7 cm^{-3} . The -10V and -20V curves are shown with open circles (PISCES data) and solid lines (Model). A region on the right is labeled "{ Doping }".

The bottom plot shows Electrostatic Potential in Volts on a linear y-axis from -1.5 to 1.5. It displays three curves for the same gate voltages V_g . The $+5\text{V}$ curve is a solid line peaking at $\sim 1.3\text{V}$. The -10V and -20V curves are shown with open circles (PISCES data) and solid lines (Model).

Common parameters for both plots are: $|X| = 0.15 \mu\text{m}$, $V_D = 0\text{V}$, and $I_{DS} = 736 \text{ A}$.

Fig. 7. The gate voltage when punchthrough of the buried channel occurs (V_{Gpt}) and the gate voltage when surface inversion starts to happen (V_{Gsi}) vs. the channel doping density of the 6H-SiC buried-channel NMOS device with a channel junction depth of $0.08\mu\text{m}$ and $0.16\mu\text{m}$, biased at $V_D = 0\text{V}$ and -6V .