Sinusoidal Steady State Analysis on 4H–SiC Buried Channel MOSFETs

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With the combined use of the drift-diffusion (DD) model, experimental measured parameters and small-signal sinusoidal steady-state analysis, we extract the Y-parameters for 4H–SiC buried-channel metal oxide semiconductor field effect transistors (BCMOSFETs). Output short-circuit current gain G and Mason’s invariant U are calculated for extrapolating unity current gain frequency in the common-source configuration fT and the maximum frequency of oscillation fmax, respectively. Here fT = 800 MHz and fmax = 5 GHz are extracted for the 4H–SiC BCMOSFETs, while the field effect mobility reaches its peak value 87 cm²/Vs when VGS = 4.5 V. Simulation results clearly show that the characteristic frequency of 4H–SiC BCMOSFETs and field effect mobility are superior, due to the novel structure, compared with conventional MOSFETs.

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Recent development[1,2] has demonstrated that SiC is a very promising electronic material, especially for use in semiconductor devices operating at high temperatures, high power, and high frequencies. Attributed to its wide band gap, large thermal conductivity, and considerable high field drift velocity, 4H–SiC polytype has been shown to have special capabilities. However, the channel mobility is extremely low in 4H–SiC MOSFETs,[3] which is believed to be due to the high density of trap scattering at the SiO₂/4H–SiC interface.[4,5] Then, buried channel MOSFETs, i.e. a novel structure for 4H–SiC devices, have been proposed in laboratory.[6] Despite the impressive progress obtained recently, neither experiment nor simulation results on high-frequency small signal analysis for above-mentioned devices, to our knowledge, has ever been reported.

In this Letter, we combine a drift-diffusion model, experimental measured parameters and sinusoidal steady-state analysis (S²A hereafter) to extract Y-parameters for the structure mentioned above. Following the extraction, characteristic frequency and field effect mobility are compared between BCMOSFETs and conventional MOSFETs for the given device parameters.

The drift diffusion (DD) model consists of Poisson’s equation and the current-continuity equations for electrons and holes. Poisson’s equation can be written in the form

\[ F_\psi(n, p) = \nabla \cdot \varepsilon \nabla \psi + q[p - n + N_D^+ - N_A^+] + \rho_e = 0, \]

with

\[ N_D^+ = \frac{N_D}{1 + g_C \times \exp[(E_F n - E_c + \Delta E_D)/kT]}, \]

\[ N_A^+ = \frac{N_A}{1 + g_V \times \exp[(E_v - E_F p + \Delta E_A)/kT]}, \]

where \( \psi, n, p, \) and \( \rho_e \) are the electrostatic potential, electron concentration, hole concentration, and surface charge density, respectively. In consideration of incomplete ionization of impurities in 4H–SiC, the ionized donor and acceptor concentrations \( N_D^+ \) and \( N_A^+ \) are treated using Fermi-Dirac statistics with degeneracy factor \( g_C \) for the conduction bands and with \( g_V \) for the valence bands by Eqs. (2) and (3).[7] The current-continuity equations can be written as

\[ F_n(n, p) = \frac{1}{q} \nabla \cdot J_n - U_n - \frac{\partial n}{\partial t} = 0, \]

\[ F_p(n, p) = \frac{1}{q} \nabla \cdot J_p - U_p - \frac{\partial p}{\partial t} = 0, \]

with

\[ J_n = q(D_n \nabla n - \mu_n n \nabla \psi), \]

\[ J_p = -q(D_p \nabla p + \mu_p p \nabla \psi), \]

where \( J_n(J_p), \mu_n(\mu_p), D_n(D_p), \) and \( U_n(U_p) \) are the electron (hole) current density, mobility, diffusivity, and total recombination rate, respectively.

Mobility model approach adopted here contains both low field mobility as well as high field mobility model. Following Ref. [8], low field mobility is given by

\[ \mu = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + (N_D^+ + N_A^+ - N_{\text{ref}})^\alpha}, \]
where $\mu_{\text{min}}$, $\mu_{\text{max}}$, $\alpha$, and $N_{\text{ref}}$ are the fitting parameters. The parameter $\mu_{\text{max}}$ in Eq. (8) represents the mobility of unintentionally doped samples with lattice scattering being the main scattering mechanism, while $\mu_{\text{min}}$ is the mobility in highly doped material with impurity scattering being dominant, $N_{\text{ref}}$ is the doping concentration at which the mobility is halfway between $\mu_{\text{max}}$ and $\mu_{\text{min}}$, and $\alpha$ is a measure of how quickly the mobility changes from $\mu_{\text{max}}$ to $\mu_{\text{min}}$.

When the electric field $E$ increases, velocity saturation effect becomes significant, and the high field mobility model should be employed in the form

$$
\mu(E) = \mu \left( \frac{1}{1 + \frac{E}{E_{\text{sat}}}} \right)^{1/\beta},
$$

(9)

where $\mu$ is the low field mobility obtained in Eq. (8) and $\bar{v}_{\text{sat}}$ is the saturation velocity ascertained from $\bar{v}_{\text{sat}} = \bar{v}_{\text{sat}}\bar{v}_{\text{sat}}$.

Substituting Eq. (10) into Eqs. (1), (4) and (5), and expanding as a Taylor series to first-order only (the small-signal approximation), we can obtain the non-linear equation for each of the three partial differential equations in the form

$$
F(\psi, n, p) = F(\psi_0, n_0, p_0) + \frac{\partial F}{\partial \psi}|_{\psi=\psi_0} \bar{\psi} e^{j\omega t} + \frac{\partial F}{\partial n}|_{n=n_0} \bar{n} e^{j\omega t} + \frac{\partial F}{\partial p}|_{p=p_0} \bar{p} e^{j\omega t}.
$$

(11)

If a valid dc solution at the desired dc bias has already been computed, then $F(\psi_0, n_0, p_0) = 0$. We can obtain the following linear system:

$$
\begin{align*}
\left( \frac{\partial F_{\psi}}{\partial \psi} \right)_{\psi=\psi_0} \bar{\psi} + \left( \frac{\partial F_{n}}{\partial n} \right)_{n=n_0} \bar{n} + \left( \frac{\partial F_{p}}{\partial p} \right)_{p=p_0} \bar{p} &= B, \\
\kappa_{22} \frac{\partial F_{\psi}}{\partial n} + \kappa_{33} \frac{\partial F_{p}}{\partial n} &= B, \\
\kappa_{22} \frac{\partial F_{n}}{\partial \psi} + \kappa_{33} \frac{\partial F_{p}}{\partial \psi} &= B,
\end{align*}
$$

(12)

where $\kappa_{22} = \frac{\partial F_{n}}{\partial \psi} - j\omega \frac{\partial}{\partial n} \left( \frac{\partial F_{p}}{\partial \psi} \right)$, $\kappa_{33} = \frac{\partial F_{p}}{\partial \psi} - j\omega \frac{\partial}{\partial p} \left( \frac{\partial F_{p}}{\partial \psi} \right)$, vector $B$ is dependent on the boundary conditions specified by the ac input voltage. Then the ac $I$–$V$ characteristics of the two-port network model for the device are obtained, so do the $Y$-parameters.

$$
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix} =
\begin{pmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{pmatrix}
\begin{pmatrix}
U_1 \\
U_2
\end{pmatrix}.
$$

(13)

With the dc bias $V_{GS} = 5\,\text{V}$, $V_{DS} = 15\,\text{V}$ applied, small sinusoidal signals are superimposed upon the ports to simulate high frequency characteristics of the aforementioned device. Real and imaginary parts of every matrix elements of $Y$-parameters are demonstrated in Fig. 2.
The output short-circuit current gain is a small signal characteristic exclusively depended on the device configuration, working frequency and bias conditions, from which unity current gain frequency in the common-source configuration, $f_T$, could be obtained as it goes to unity.

$$G = H_{21} = \frac{Y_{21}}{Y_{11}}.$$  \hspace{1cm} (14)

Additionally, a figure of merit that has been used extensively for microwave characterization is Mason’s invariant (or unilateral power gain), which was originally defined by Mason.$^{[12,13]}$

$$U = \frac{|Y_{21} - Y_{12}|^2}{4[\text{Re}(Y_{11})\text{Re}(Y_{22}) - \text{Re}(Y_{12})\text{Re}(Y_{21})]}.$$  \hspace{1cm} (15)

Provided that the $Y$-parameters have been acquired, $G$ and $U$ are calculated and drawn for both BCMOSFETs and conventional MOSFETs in Fig. 3. Unity current gain frequency in the common-source configuration could be readily read in the intersection points between the $G$ curves and the frequency axis. For BCMOSFETs, $f_T$ reaches 800 MHz, while for the conventional ones only 70 MHz. With the $U$ curves extrapolated to the frequency axis, $f_{\text{max}}$ is extracted for the buried channel novel structure as 5 GHz, and for the conventional ones only 0.2 GHz.

In addition to the above advantage of frequencies, BC novel structure’s superiority also demonstrated on its mobility performs documented by both experimental data$^{[14,15]}$ and our results. With the electron acceptor fast interface state density of $5 \times 10^{11}$ cm$^{-2}$ eV$^{-1}$ added as the boundary condition in the simulation, mobilities for both BCMOSFET and conventional MOSFET, which have the same structure parameters, versus $V_{GS}$ are sketched in Fig. 4.

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**Fig. 2.** $Y$-parameters versus frequency for the simulated structure.

**Fig. 3.** $U$ and $G$ versus frequency for both the buried channel MOSFETs and the conventional MOSFETs within the interested frequencies domain.
The maximum field effect mobility value is 87 cm$^2$/Vs when $V_{GS} = 4.5$ V for the BC ones and 41 cm$^2$/Vs for the conventional ones in the same gate bias.

![Field effect mobility versus $V_{GS}$ for both the BC-MOSFETs and the conventional MOSFETs, with $V_{DS} = 10$ V.](image)

Thanks to the novel structure employed by the device, BCMOSFETs do provide frequency and mobility advantages for high-frequency and high-speed applications, which also fulfill its design purpose.

In summary, in the combination of the drift-diffusion (DD) model, experimental measured parameters and small-signal sinusoidal steady-state analysis, we have extracted the $Y$-parameters for 4H-SiC BCMOSFETs. Here $f_T = 800$ MHz and $f_{max} = 5$ GHz are extracted for the simulated structure by means of the extrapolation of output short-circuit current gain $G$ and Mason’s invariant $U$, respectively. With the field effect mobility reaches its peak value 87 cm$^2$/Vs for $V_{GS} = 4.5$ V, sound ac characteristics are obtained. Simulation results clearly show that the 4H-SiC BCMOSFETs do have an advantage in high-frequency and high-speed applications due to their characteristic frequency and field effect mobility superiority compared to the conventional MOSFETs.

References