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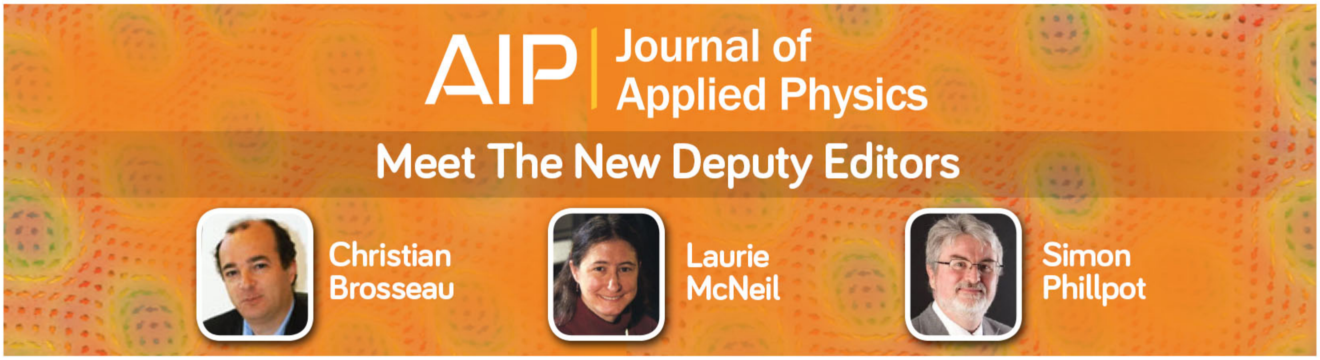

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Low frequency noise in GaN metal semiconductor and metal oxide semiconductor field effect transistors

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The low frequency noise in GaN field effect transistors has been studied as function of drain and gate biases. The noise dependence on the gate bias points out to the bulk origin of the low frequency noise. The Hooge parameter is found to be around 2×10^{-3} to 3×10^{-3}. Temperature dependence of the noise reveals a weak contribution of generation–recombination noise at elevated temperatures. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1372364]

I. INTRODUCTION

A recent report on GaN highly doped metal semiconductor field effect transistors (HD-MESFETs)[1] showed that these devices (especially short channel MESFETs) have a potential to compete with conventional AlGaN/GaN heterostructure field effect transistors (HFETs). One of the most important parameters of the microwave transistors is the level of the low frequency noise, which determines the device suitability for microwave applications.

In this article, we present the experimental results on the bias and temperature dependence of the low frequency noise in HD-MESFETs and in GaN thin channel highly doped metal oxide semiconductor field effect transistors (HD-MOSFETs). The analysis of the noise gate voltage dependence allows us to speculate about the noise sources location. The experimental results are compared with the noise data for bulk GaN and for AlGaN/GaN HEFTs.

II. EXPERIMENTAL DETAILS

The structures were grown by low-pressure metal organic chemical vapor deposition on (0001) sapphire substrates. The deposition of approximately 2 μm of nominally undoped GaN was followed by the growth of a Si-doped GaN channel. The thickness and doping level of the channel (extracted from capacitance–voltage characteristics) were $\sim$60 nm and $10^{18}\,\mathrm{cm}^{-3}$, respectively. The measured electron Hall mobility in the channel was close to $\mu=100\,\mathrm{cm}^2/\mathrm{V\,s}$. Prior to the HD-MOSFET fabrication, a 7nm SiO_2 layer was deposited on a part of the heterostructures using plasma enhanced chemical vapor deposition.

The fabricated HD-MESFETs and HD-MOSFETs had the source–drain spacing of 4 μm and the gate length of 1.5 μm.

A low-frequency noise was measured in the frequency range from 1 Hz to 100 kHz with the sources grounded. We used the probe station with the tungsten probes of 10 μm diameter. A controlled pressure on the probes provided the contacts to the sample pads.

III. RESULTS AND DISCUSSION

The current–voltage characteristics of the HD-MESFETs and HD-MOSFETs were similar and differed only in the threshold voltage, V_{th}, which was $V_{\mathrm{th}}=(-4\div-5)$ V and $V_{\mathrm{th}}=(-7\div-8)$ V for HD-MESFETs and HD-MOSFETs, respectively. Figure 1 shows the current–voltage characteristic of the HD-MESFET. The gate leakage current also shown in Fig. 1 did not exceed $I_g=10\,\mathrm{nA}$ at drain bias $V_d=8$ V and gate bias $V_g=5$ V for both types of transistors. The measurements using transmission line model (TLM) structures showed that the contact resistance R_c was negligible compared with the channel resistance.

The capacitance voltage measurements on the test structure with a relatively large area of the Schottky contact indicated that the doping profile of the GaN layer was uniform with doping density of $N_d\approx10^{18}\,\mathrm{cm}^{-3}$. The built-in voltage of the Schottky barrier was found to be $V_{\mathrm{bi}}\approx1$ V.

The noise spectra of drain current fluctuations S_{Id} had the form of $1/f^{\Gamma}$ noise with Γ close to unity ($\Gamma=1.0$–1.15) for both HD-MESFETs and HD-MOSFETs. At low drain biases, $V_d<1$ V, the spectral noise density S_{Id} was proportional to the square of the drain voltage $S_{Id}\sim V_d^2$, as expected.

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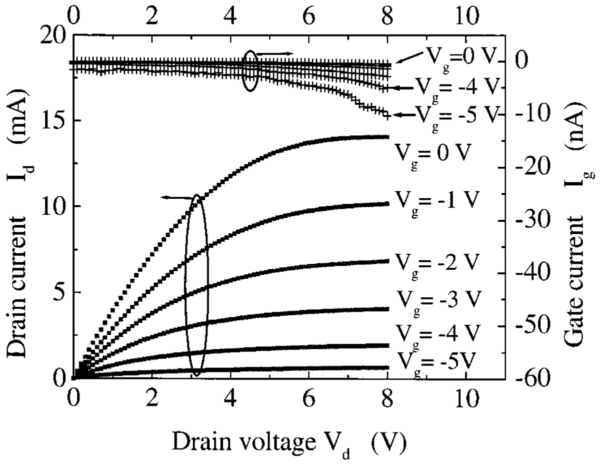

FIG. 1. Current–voltage characteristics of the MESFET under investigation. Crosses show the gate leakage current.

The noise temperature dependence revealed a weak contribution of one or two local levels. Figure 2 shows the temperature dependence of noise for one of the HD-MESFETs. As seen, the weak noise maxima shifted to higher temperatures with a frequency increase. This behavior is typical for the generation–recombination ($g-r$) noise from a local level.[2] However, the contribution of $g-r$ noise was too weak compared to the $1/f$ noise in order to extract the local level parameters.

Many different noise sources in FETs might be important including the contribution of the gate leakage current, contact noise, bulk noise, surface noise, and the fluctuations of the Schottky barrier space charge region (SCR) width, W (see Fig. 3). Depending on the device structure, different noise mechanisms are responsible for the main contribution to the overall noise.[3–5] Since the observed low frequency noise was a superposition of the $1/f$ and generation–recombination noise, we should analyze the possible location of the noise sources on the basis of both $1/f$ and $g-r$ noise models.

A. Contribution to noise from gate leakage current

The gate leakage current in the MESFETs and MOSFETs under investigation did not exceed a few nanoamperes in the linear regime of operation (see Fig. 1) and was 6–7 orders of magnitude smaller than the drain current. Hence, the gate leakage current should not contribute much to the output noise in these devices.[6–8]

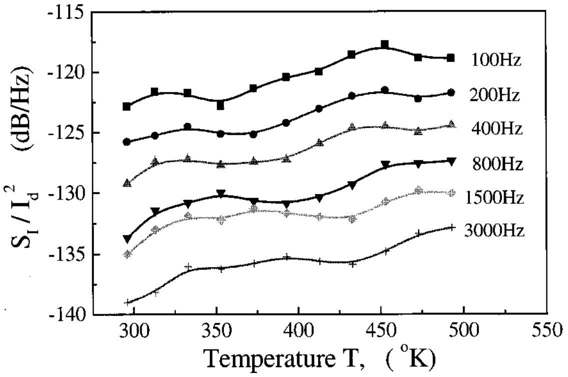

FIG. 2. Temperature dependence of noise S_I/I_d^2 for MESFET at different frequencies of analysis.

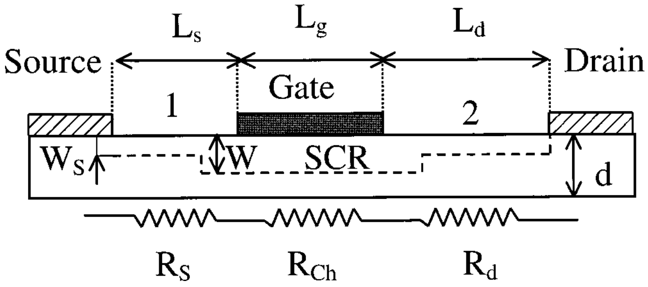

FIG. 3. The schematic view of the HD-MESFET. Also shown a simplified equivalent drain-to-source circuit, $R_{\mathrm{ds}}=R_s+R_d$.

B. Contact contribution to noise

In order to determine the contribution of the contact noise to the measured noise spectra, the noise measurements were performed on the TLM structures. Assuming that the contribution of the contact noise and of the noise from the GaN layer are not correlated and taking into account that the contact resistance is much smaller than the resistance of the GaN layer, the spectral noise density of the current fluctuations S_I/I^2 can be expressed as:

$$\frac{S_I}{I^2}=\frac{S_{\mathrm{Rc}}+S_{\mathrm{GaN}}}{R_{\mathrm{GaN}}^2}, \tag{1}$$

where S_{Rc} and S_{GaN} are the spectral noise densities of the contact resistance and of the GaN layer resistance fluctuations, respectively, R_{GaN} is the resistance of the GaN layer between the pads of the TLM structure. In the limiting case when the contact noise dominant ($S_{\mathrm{Rc}}\gg S_{\mathrm{GaN}}$), the spectral noise density, S_I/I^2, should be proportional to L_I^{-2}, where L_1 is the distance between the TLM contact pads:

$$\frac{S_I}{I^2}=\frac{S_{\mathrm{Rc}}}{R_{\mathrm{GaN}}^2}\propto\frac{1}{L_1^2}. \tag{2}$$

In the opposite limiting case, when $S_{\mathrm{Rc}}\ll S_{\mathrm{GaN}}$, the spectral noise density of the GaN layer resistance fluctuations is proportional to the reciprocal volume of the GaN layer (the bulk origin of the noise) or to the reciprocal GaN area (surface origin of the noise) between the contact pads. In both these cases:

$$\frac{S_I}{I^2}=\frac{S_{\mathrm{GaN}}}{R_{\mathrm{GaN}}^2}\propto\frac{1}{L_1}. \tag{3}$$

Figure 4 shows the dependence of the relative spectral noise density of the current fluctuations on the distance L_1 between the pads of the TLM structure. Since this dependence is close to the $1/L_1$ law, we conclude that contacts do not contribute much to the overall noise.

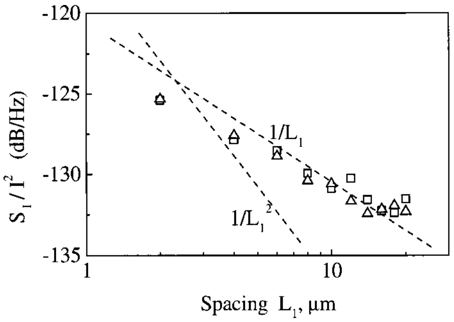

FIG. 4. The dependence of the relative spectral noise density S_I/I^2 on the distance L_I between the pads of TLM structure. Frequency of analysis $f = 200$ Hz.

C. Surface noise sources

Let us first consider the location of the noise sources at the surface of GaN in source-gate and drain-gate regions. One of the possible mechanisms of the surface $g-r$ noise was analyzed in Ref. 9 (the $1/f$ noise originated from the surface is often dominant in Si MOSFETs).[10]

For the noise sources located at the surface of regions 1 and 2 in Fig. 3, the relative spectral noise density of the short circuit drain current fluctuations can be presented in the following form:

$$\frac{S_{Id}}{I_d^2} = \frac{S_{\mathrm{Rds}}}{R_{\mathrm{ds}}^2} \frac{R_{\mathrm{ds}}^2}{(R_{\mathrm{ds}}+R_{\mathrm{Ch}})^2}, \tag{4}$$

where R_{Ch} is the channel resistance which depends on the gate voltage, V_g, $R_{\mathrm{ds}} = R_d + R_s$ is the resistance of source-gate and drain-gate regions (regions 1 and 2 in Fig. 3), S_{Rds} is the spectral noise densities of the R_{ds} fluctuations. In this case, the noise gate voltage dependence is determined by the dependence of R_{Ch} on V_g.

The data points in Fig. 5 correspond to the experimental results for the dependence of noise on the drain current for HD-MESFETs and HD-MOSFETs at a constant drain bias. Within an experimental error, the noise behavior for both types of transistors was identical. This indicates that SiO_2 film deposited in order to fabricate HD-MOSFETs does not affect much the noise properties. As seen from Fig. 5, the relative spectral noise density S_{Id}/I_d^2 decreases with the drain current increase, i.e. with the gate voltage increase.

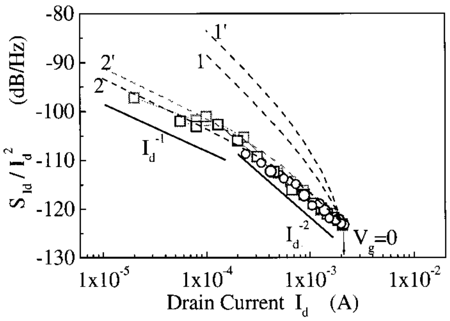

FIG. 5. The dependence of the of the relative spectral noise density of the drain current fluctuations on drain current. Drain voltage $V_d = 0.5$ V. Frequency of analysis $f = 200$ Hz. Different symbols show data for MESFETs and MOSFETs. Lines 1 and 1′ are calculated according to the Lauritzen model (see Ref. 11) [Eq. (10)] for $R_{\mathrm{ds}} = 115\ \Omega$ and $R_{\mathrm{ds}} = 180\ \Omega$, respectively. Lines 2 and 2′ are calculated according Eq. (14) for $R_{\mathrm{ds}} = 115\ \Omega$ and $R_{\mathrm{ds}} = 180\ \Omega$, respectively (bulk origin of noise).

According to Eq. (4), noise S_{Id}/I_d^2 should decrease with the R_{Ch} increase, i.e., with the drain current decrease. Since the experimental dependence exhibits the opposite trend, the measured noise can not be explained by the surface noise.

D. Fluctuations of the Schottky barrier SCR

Another mechanism of a low frequency noise was analyzed by Lauritzen.[11] He assumed that the fluctuations of the charge state of the levels inside the depletion region of a p-n junction or of a Schottky barrier result in the fluctuations of the depletion region width, W, and, consequently, in the fluctuations of the channel width and the channel resistance. For zero free carrier concentration in the depletion region and for a single time constant process contributing to noise, the expression for the equivalent gate voltage fluctuations S_{Vg} derived in Ref. 11 for the linear mode of operation is given by

$$S_{Vg} = A \frac{W^3 \tau}{1+\omega^2\tau^2}, \tag{5}$$

where A is the parameter which does not depend on gate voltage, $\omega = 2\pi f$, f is the frequency, and τ is the fluctuation time constant. The $g-r$ noise of this origin was recently observed in GaAsFETs[5] (the superposition of noise from several traps can result in the $1/f$-like spectrum).

The spectral noise density of the channel resistance fluctuations is given by

$$\frac{S_{\mathrm{RCh}}}{R_{\mathrm{Ch}}^2} = \frac{S_{Vg} g^2}{I_d^2}, \tag{6}$$

where g is the intrinsic transconductance. In the linear regime, the transconductance is inversely proportional to the depletion region width, W. Therefore, the dependence of the relative spectral noise density of the channel resistance fluctuations on the channel width W can be expressed as:

$$\frac{S_{\mathrm{RCh}}}{R_{\mathrm{Ch}}^2} = B \frac{W}{I_d^2}. \tag{7}$$

The spectral noise density of the short circuit drain current fluctuations can be presented in the following form:

$$\frac{S_{Id}}{I_d^2} = \frac{S_{\mathrm{Rch}}}{R_{\mathrm{Ch}}^2} \frac{R_{\mathrm{Ch}}^2}{(R_{\mathrm{ds}}+R_{\mathrm{ch}})^2} = \frac{BWR_{\mathrm{Ch}}^2}{(R_{\mathrm{ds}}+R_{\mathrm{ch}})^2 I_d^2}, \tag{8}$$

where B is the parameter which does not depend on the gate voltage.

In order to compare our experimental results (Fig. 5) with this model, the SCR width, W, should be expressed as a function of the drain current:

$$W = \frac{(I_{\mathrm{fc}} - I_d) W_0}{(I_{\mathrm{fc}} - I_{d0})}, \tag{9}$$

where I_{d0} and W_0 are drain current and depletion region thickness, at $V_g = 0$, respectively, I_{fc} is the full channel drain current.

The substitution of Eq. (9) into Eq. (8) yields the dependence of noise on the drain current at the constant drain voltage:

$$\frac{S_{Id}}{I_d^2}=B\frac{(I_{\text{fc}}-I_d)(V_d/I_d-R_{\text{ac}})^2W_0}{(I_{\text{fc}}-I_{d0})V_d^2}. \tag{10}$$

In Fig. 5, lines 1 and 1′ are calculated using Eq. (10) for $R_{\text{ds}}=115\,\Omega$ and $R_{\text{ds}}=180\,\Omega$, respectively (see Appendix for R_{ds} estimates). In order to calculate the dependence of noise on the drain current, parameter B was adjusted to fit the noise value at $V_g=0$. The thickness of the depletion region at $V_g=0$ was taken to be $W_0=0.03\,\mu$m (extracted from the capacitance–voltage measurements).
Figure 5 shows that this noise mechanism predicts a much faster increase of noise compared with that observed experimentally.

E. Bulk location of the noise sources

Van der Ziel[12] assumed that fluctuations of the carrier density in the channel are responsible for the noise in FETs. Assuming that a single time constant process contributes to noise and neglecting the influence of resistance R_{ds} on noise, the spectral noise density of drain current fluctuations determined by this mechanisms are given by:[12]

$$S'_{Id}=\frac{4I_dV_dq\mu\gamma\tau_1}{I_g^2(1+\omega^2\tau_1^2)}, \tag{11}$$

where q is the electronic charge, μ is the electron mobility, γ is constant, L_g is the gate length, and τ_1 is the fluctuation time constant.

For the linear regime of operation, Eq. (11) can be simplified:

$$\frac{S'_{Id}}{I_d^2}=\frac{S_{\text{RCh}}}{R_{\text{Ch}}^2}=\frac{4\gamma\tau_1}{N_{\text{Ch}}(1+\omega^2\tau_1^2)}, \tag{12}$$

where N_{Ch} is the number of electrons in the channel. A superposition of noise from several traps or from a continuous spectrum of levels results in the $1/f$ like noise.[13] Equation (12) takes into account only the noise sources located inside the channel. Assuming that the noise sources are not correlated and located both in the channel and in the lateral regions 1 and 2 (see Fig. 3),[14,15] the spectral noise density of the drain current fluctuations can be presented in the following form:

$$\frac{S_{Id}}{I_d^2}=\frac{S_{\text{Rds}}}{R_{\text{ds}}^2}\frac{R_{\text{ds}}^2}{(R_{\text{ds}}+R_{\text{ch}})^2}+\frac{S_{\text{RCh}}}{R_{\text{Ch}}^2}\frac{R_{\text{Ch}}^2}{(R_{\text{ds}}+R_{\text{ch}})^2}. \tag{13}$$

In Eq. (12), N_{ch} is the only parameter which depends on the gate voltage V_g. In the linear regime of operation, the number of electrons in the channel is inversely proportional to the channel resistance ($N_{\text{ch}}\sim 1/R_{\text{ch}}$). Hence, the expression for the spectral noise density of the drain current fluctuations is given by:

$$\frac{S_{Id}}{I_d^2}=\frac{S_{\text{Rds}}}{R_{\text{ds}}^2}\frac{R_{\text{ds}}^2}{(R_{\text{ds}}+R_{\text{ch}})^2}+\frac{CR_{\text{Ch}}^3}{(R_{\text{ds}}+R_{\text{ch}})^2}. \tag{14}$$

where C is a parameter, which does not depend on gate voltage.

The bulk noise originated from the regions 1 and 2 in Fig. 3 should be of the same nature as the channel bulk noise. Therefore the spectral noise density $S_{\text{Rds}}/R_{\text{ds}}^2$ is given by

$$\frac{S_{\text{Rds}}}{R_{\text{ds}}^2}=\frac{\Phi_{\text{Ch0}}}{\Phi_{\text{ds}}}\left(\frac{S_{\text{RCh}}}{R_{\text{Ch}}^2}\right)_{V_g=0}, \tag{15}$$

where $\Phi_{\text{Ch0}}=(d-W_0)L_gZ$, is the channel volume at $V_g=0$, d is the full channel thickness, Z is the channel width, and Φ_{ds} is the volume of GaN layer between source-gate and gate-drain intervals (regions 1 and 2 in Fig. 3). We estimated Φ_{ds} as $\Phi_{\text{ds}}=(d-W_0)(L_d+L_s)Z$ for $R_{\text{ds}}=180\,\Omega$ and $\Phi_{\text{ds}}=d(L_d+L_s)Z$ for $R_{\text{ds}}=115\,\Omega$ (see Appendix for R_{ds} estimates).

Curves 2 and 2′ in Fig. 5 are calculated using Eq. (14) for $R_{\text{ds}}=115\,\Omega$ and $R_{\text{ds}}=180\,\Omega$, respectively. As can be seen from Fig. 5, the experimental data can be fitted quite well using the bulk noise model. At a low drain current, $(S_{Id}/I_d^2)\sim I_d^{-1}$. This reflects the fact that the noise depends on the channel volume as $1/\Phi_{\text{Ch}}$ [see Eq. (14)]. This is a usual behavior of the bulk $1/f$ noise. At high drain currents and small gate voltages, the dependence of noise on drain current is close to $(S_{Id}/I_d^2)\sim I_d^{-2}$.

Since it appears that the noise sources in the transistors under investigation are located in the bulk of GaN layer, the Hooge parameter $\alpha=(S_I/I^2)Nf$ (N is the total number of carriers in the sample) can be used to characterize the noise level.[16] We estimated $\alpha=(2-3)\times 10^{-3}$ for the entire range of the gate voltages. These values of α are at least one order of magnitude smaller than those reported for bulk GaN[17] and 3–5 orders of magnitude smaller than that recently reported for p-type GaN.[18] The α values for HD-MESFETs and HD-MOSFETs found in the present article are comparable with α values for AlGaN/GaN HFETs.[6,19,20]

IV. CONCLUSION

The measurements of the low frequency noise on GaN HD-MESFETs and HD-MOSFETs showed that the noise properties of MESFETs and MOSFETs are identical and that the drain and source contacts do not contribute much to the low frequency noise. The dependence of the noise on gate voltage indicates that the noise originates from the bulk of GaN in the channel and in the source to gate and drain to gate regions. We estimated the Hooge parameter $\alpha=(2-3)\times 10^{-3}$. This value is about one order of magnitude smaller than the value of α reported for bulk n-type GaN. The temperature dependence of noise shows a weak contribution of $g-r$ noise at elevated temperatures.

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APPENDIX

From Fig. 3, we find

$$R_{\rm ds}=R_d+R_s=\frac{R_0}{1+\dfrac{L_g(d-W_s)}{(L_d+L_s)(d-W_0)}},$$

where $R_0 \approx 250\,\Omega$ and $W_0=0.03\,\mu$m are the output resistance and depletion region thickness W at $V_g=0$. This equation yields $R_{\rm ds}\approx 115\,\Omega$ for $W_s=0$ and $R_{\rm ds}\approx 160\,\Omega$ for $W_s=W\approx 0.03\,\mu$m.

Resistance $R_{\rm ds}$ can also be estimated from the transistor dc characteristics. The gate voltage dependence of the output resistance $R_{\rm out}$ is given by (see Ref. 21, for example):

$$R_{\rm out}=\frac{R_0}{1-\sqrt{\dfrac{V_{\rm bi}-V_g}{V_{\rm po}}}}+R_{\rm ds},$$

where $V_{\rm po}$ is the pinch-off voltage.

The intercept of the dependence of $R_{\rm out}$ on

$$\left(1-\sqrt{\frac{V_{\rm bi}-V_g}{V_{\rm po}}}\right)^{-1}$$

should yield the value of $R_{\rm ds}$. The accuracy of this procedure is limited, since this technique is very sensitive to the values of $V_{\rm bi}$ and $V_{\rm po}$. This method yields $R_{\rm ds}\approx 115$–$180\,\Omega$.

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