Monte Carlo study of the noise performance of isolated-gate InAs/AlSb HEMTs

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Abstract— In this work, the extrinsic dynamic behaviour and noise performance of a 225 nm isolated-gate InAs/AlSb HEMT have been studied by means of Monte Carlo simulations. A very good agreement with experimental results has been achieved for f_T. Discrepancies between experimental and simulated f_{max} have been observed and attributed to the experimental frequency dispersion of g_d and C_{ds}. The simulations of the intrinsic and extrinsic noise parameters indicate an excellent performance for this device (F_{min}=0.3 dB@10 GHz) even if we confirm that the presence of the native oxide under the gate induces an significant decrease in f_T and f_{max} of around 20%, together with an increase of noise figure and noise resistance.

I. INTRODUCTION

InGaAs/InAlAs High Electron Mobility Transistors (HEMTs) are for the moment the best option for low-noise high-frequency applications, providing higher cut off frequencies than any other devices [1,2]. Because of the excellent transport properties of InAs, its very high mobility and peak velocity, together with the very high offset in the conduction band between InAs and AlSb (ΔEc=1.35 eV), the InAs/AlSb material system has become a very promising substitute of InGaAs/InAlAs for improving the high-frequency, low-noise behavior of HEMTs [3]. One of the main drawbacks of this novel material system is the relatively high gate leakage current. This leakage has been reduced introducing a native oxide under the gate [4]. From now, we will call these devices isolated-gate AlSb/InAs HEMTs (IG Sb-HEMTs).

In previous works, we have studied the static and intrinsic small signal equivalent circuit (SSEC) performance of these IG Sb-HEMTs by means of Monte Carlo (MC) simulations [5,6]. The validity of our model was verified by comparing with experimental data. Due to the high-frequency, low-noise target applications of IG Sb-HEMTs, the extrinsic high frequency performance and noise behavior warrant further study.

In this work we present a study of the extrinsic dynamic performance, together with intrinsic and extrinsic noise behavior of IG Sb-HEMTs by means of MC simulations. The influence of the native oxide under the gate has also been studied by comparing the simulation results for the IG Sb-HEMT with those obtained by the simulation of a traditional Schottky-gate (SG) HEMT with the same topology as the IG but without the native oxide under the gate.

II. DEVICE DESCRIPTION

To allow the comparison of simulation results with experimental data the simulated device has been modeled as similar as possible to the experimental IG Sb-HEMT [4,7]. In order to study the influence of the native oxide in the performance of the device, two transistors with the same epitaxial structure have been simulated: one IG and one standard SG Sb-HEMT (Fig. 1). The epitaxial stack for both devices was built up by an AlSb buffer of 800 nm followed by an InAs channel of 15 nm and a 15 nm thick AlSb barrier. An $In_{0.5}Al_{0.5}As$ protection layer of 4 nm is located upon the barrier, followed by a 5 nm highly doped InAs cap layer (N_D=5×10^{18} cm^{-3}). A δ–doping layer of 4.5×10^{12} cm^{-2} is located 5 nm far from the channel.

In order to account for the interface states and reproduce the experimental Hall n_s, a negative surface charge with a value σ/e=-2.8x10^{12} cm^{-2} has been considered. Due to the fabrication process, the negative surface charge at the top of the recessed part of the device can be different from the one in the top of the cap layer [8]. We have observed in previous works that in our simulations σ_{recess} can be considered as a free parameter as it only introduces an offset in the threshold voltage [5]. We have adopted a value of σ_{recess}/e=-1.2x10^{12} cm^{-2}.

The only difference between the IG and SG devices is that in the case of the IG transistor there is a native oxide under the gate. The oxidation of AlSb is a very complex process, making it difficult to predict the thickness and dielectric constant of the formed native oxide. After comparing the simulation results with experimental data for different values of the dielectric constant and the thickness of the oxide, we have considered a 2 nm thick oxide with dielectric constant of 2.2, corresponding to Al(OH)3[5].

III. SIMULATION MODEL

The extrinsic dynamic performance and noise behavior of Sb-HEMTs has been studied by MC simulations. A semiclassical ensemble MC consistently coupled with a two dimensional Poisson solver has been used. This simulator has been proven to be a powerful and accurate simulation technique to study the noise performance of InP HEMTs [9]. The simulator has been modified to properly model this new InAs/AlSb material system [10], providing very good results for static behaviour and SSEC [5].

Impact ionization mechanisms are not considered in this version of the simulator since we will consider V_{DS}=0.2 V, where noise figure is expected to be minimum [7] and impact ionization is negligible [6].

For the analysis of the extrinsic dynamic and noise performance of the device, experimental values of the extrinsic parameters have been included. We have considered the experimentally extracted values [7]: L_s=3 pH, L_g=3.3 pH, L_d=4.2 pH, C_{pg}=20.2 fF, C_{pd}=18.6 fF, R_g =1 Ω. For R_s and R_d we have considered the values previously used for comparing our intrinsic DC curves with the extrinsic experimental ones: R_s=0.13 Ω·mm and R_d=0.38 Ω·mm [5].

IV. EXTRINSIC DYNAMIC PERFORMANCE

Once intrinsic dynamic performance has been studied [5], the extrinsic cutoff frequency f_T and the maximum frequency of oscillation f_{max} have to be determined. Simulation results for f_T and f_{max} have been obtained through current gain $|H_{fe}|^2$ and unilateral power gain U. They are obtained by using the frequency dependent Y-parameters coming out from the MC simulations, not from any equivalent circuit approach, in other words, $|H_{fe}|^2$ and U are direct results from the simulations [11].

From now, we will always consider V_{DS}=0.2 V, where the noise figure is close to optimum. In our simulations we have not considered the mechanisms leading to gate leakage current, I_G. So, to account for its influence in U, a gate-drain resistance and a gate-source resistance, r_{gd} and r_{gs}, in parallel with C_{gd} and C_{gs}, respectively, have been introduced externally in the SSEC [11]. We have used the experimental values of r_{gd} and r_{gs}, 12 KΩ and 14.6 KΩ [7]. The effect that the introduction of these resistances has in U and in the stability factor K at the lower frequencies is observed in Fig. 2, leading to a quite good agreement with the experimental behavior of U and K [7].

Fig. 3 shows the dependence of $|H_{fe}|^2$ and U on frequency. As observed, the effect of the gate leakage current modifies the -20dB slope of U for low frequency, but it does not affect the value of f_{max}. In the case of $|H_{fe}|^2$, its value is not affected by gate leakage. For the higher frequencies, neither the SSEC nor the values of the extrinsic parameters are valid anymore, so f_T has been obtained by linear interpolation of the low frequency -20dB slope [11].

The simulated values of f_T and f_{max} as a function of the drain current for V_{DS}=0.2 V have been compared with the experimental results in Fig. 3. While a very good agreement has been obtained for f_T, strong discrepancies appear when trying to reproduce the experimental f_{max}. These discrepancies appears due to a previous disagreement already found when comparing the experimental and simulated g_d and C_{ds} due to presence of a frequency dispersion in the experimentally extracted values [5]. The value of f_T is much lower to that obtained with InGaAs channels (around 200 GHz [12]), and the expected improvement with respect to that technology is not observed. We attribute the degradation to the non mature status of the Sb-HEMT technology.

The influence of the presence of a native oxide in order to decrease the gate leakage current has been studied by comparing the simulation results for the IG Sb-HEMT with those obtained for the SG one, Fig 4. As can be observed, the presence of the oxide isolates the gate and deteriorates the high frequency performance of the device, thus lowering significantly the values of both f_T and f_{max} (from about 230 and 130 GHz to 200 and 100 GHz).

V. INTRINSIC NOISE

To characterize the intrinsic noise, the frequency dependent spectral densities of drain and gate current fluctuations and its cross-correlation have been obtained directly from the MC simulations. Intrinsic dimensionless noise parameters P, R and C can be easily obtained from spectral densities and Y parameters [9]. We remind that P and R are a measure of the noise in the drain and gate current respectively, and C is the correlation between gate and drain current. The uncertainty in the calculation of the gate current noise leads to not very precise values for R and C. Fig. 5 shows the noise parameters as a function of drain current for the IG Sb-HEMT compared with the SG Sb-HEMT. P, R and C are practically frequency independent up to more than 50 GHz, as can be seen in the insets of Fig. 5.

The values of P, R and C in the 225 nm gate length IG Sb-HEMT (device under study) are similar to those obtained in InGaAs HEMTs with a much shorter gate of 100 nm [9], only with a slight degradation of R (due to the larger size of the gate). When comparing P, R and C between the IG and SG Sb-HEMTs, a degradation of the noise parameter P can be observed (Fig. 5) in the IG device due to the existence of the native oxide under the gate, which, on the other hand, reduces R in a wide range of drain currents.

VI. EXTRINSIC NOISE

From a practical viewpoint, it is much more useful to describe the noise behavior by the extrinsic noise parameters, like minimum noise figure, NF_{min}, noise resistance, R_n, and associated gain, $G_{ass.}$ Fig. 6 shows the values of these parameters for the IG and SG Sb-HEMT for two different frequencies: 10 GHz and 94 GHz. Experimental data for NF_{min} and G_{ass} for I_D around 50 mA/mm at a frequency of 10 GHz [7] are also included in the same graph.

A very good agreement with the experimental data has been obtained for NF_{min} [Fig.6 (a)], but an overestimation of the simulated G_{ass} is observed [Fig. 6(b)]. This overestimation is related to the previous discrepancies due to experimental frequency dispersion of some parameters in the equivalent circuit, which also induced the discrepancies in f_{max}.

It is to be noted that the noise performance of this 225 nm gate IG Sb-HEMT (Fig. 6) is comparable to that obtained for a InP HEMT with a much lower gate length, 100 nm [9], in spite of its much lower cutoff frequencies, thus showing the potential of this material system, InAs/AlSb, to replace InGaAs/AlInAs.

When comparing the IG and the SG Sb-HEMTs, it can be noticed that the presence of the native oxide induces a small decrease in G_{ass} of around 2dB and an increase in NF_{min} and R_n. However, as stated before, the mechanisms at the origin of the gate leakage current are not considered here and therefore this result may be different (mainly affecting at the lower frequencies) if those phenomena are included. In any case the interest of these MC simulations is that we have quantitatively determined the degradation that should be expected from the introduction of a gate oxide in order to check whether it is counteracted or not by the improvement of the dynamic and noise performances obtained by the reduction of the gate leakage current (that can only be determined experimentally).

VII. CONCLUSIONS

The extrinsic dynamic performance and noise behavior of a 225 nm gate InAs/AlSb HEMT has been studied by means of Monte Carlo simulations. The influence of the native oxide, whose appearance has been promoted in order to decrease gate leakage current, has been also analyzed. A degradation of the dynamic performance and noise behaviour has been observed because of the presence of the native oxide under the gate.

While a very good agreement has been obtain when comparing the simulation results for f_T with the experimental data, strong discrepancies appear for f_{max} due to the experimental frequency dispersion of g_d and C_{ds}. This problem is also present when trying to reproduce the experimental gain associated to the minimum noise figure conditions. A promising noise performance has been found for these 225 nm gate Sb-HEMT, better than that of InP devices with gate length of 100 nm, even if the cutoff frequencies are lower.

VIII. ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1. Scheme of the simulated devices.

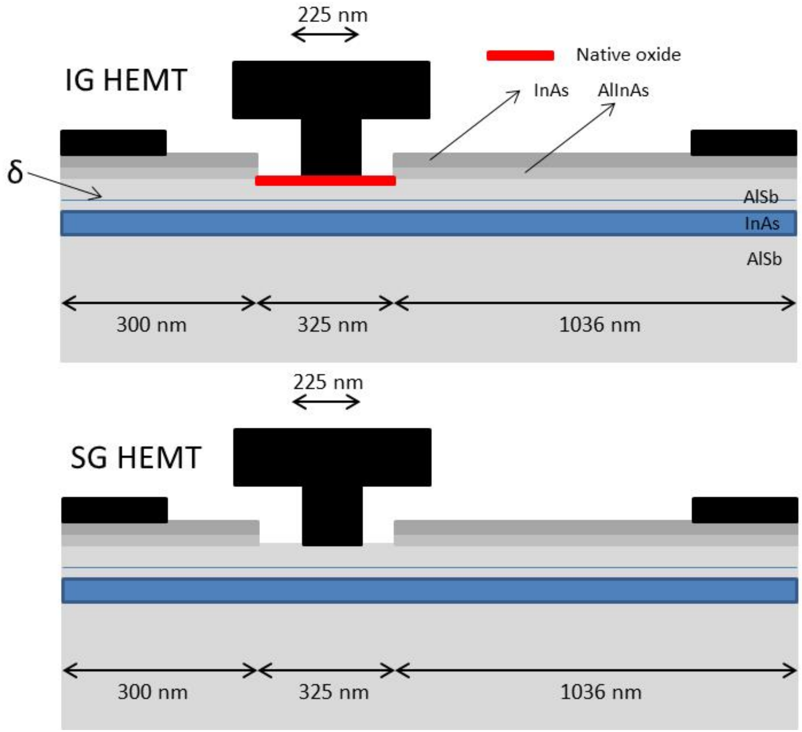
Figure 2. MC results for the frequency dependence of (a) *U* and (b) *K*, with (red triangles) and without (green circles) considering r_{gd} and r_{gs} in the the IG Sb-HEMT. V_{DS}=0.2 V and I_D=50 mA/mm.

Figure 3. (a) MC results for the frequency dependence of *U* (red circles) and $|H_{fe}|^2$ (red triangles) for I_D=50 mA/mm; the values of f_T and f_{max} are also indicated. (b) Simulation results for f_T (red triangles solid line) and f_{max} (blue circles dashed lines) for different I_D compared with the experimental data (red solid line for f_T, and blue dashed line for f_{max}). Everything for the IG Sb-HEMT for V_{DS}=0.2 V

Figure 4. Comparison between MC simulation results of f_T (circles) and f_{max} (triangles) for IG (red dashed lines) and SG Sb-HEMTs (green solid lines) for different values of I_D and V_{DS}=0.2 V.

Figure 5. MC results for the intrinsic noise parameters for 10GHz (a) *P*, (b) *R* and (c) *C* in the IG Sb-HEMT (red circles solid lines) compared with the SG Sb-HEMT (green triangles, dashed lines), all as function of I_D at V_{DS}=0.2 V. In the inset, frequency dependence of *P*, *R* and C around I_D=50 mA/mm.

Figure 6. Comparison between the simulation results for the IG Sb-HEMT (red circles) and the SG ones (green triangles). (a) Minimum noise figure, NF_{min}, (b) associated gain, G_{ass} and (c) noise resistance, R_n, as a function of the drain current for two different frequencies 19 GHz (solid lines) and 94 GHz (dashed lines). The available experimental data at 10 GHz are also included (yellow stars) [7].



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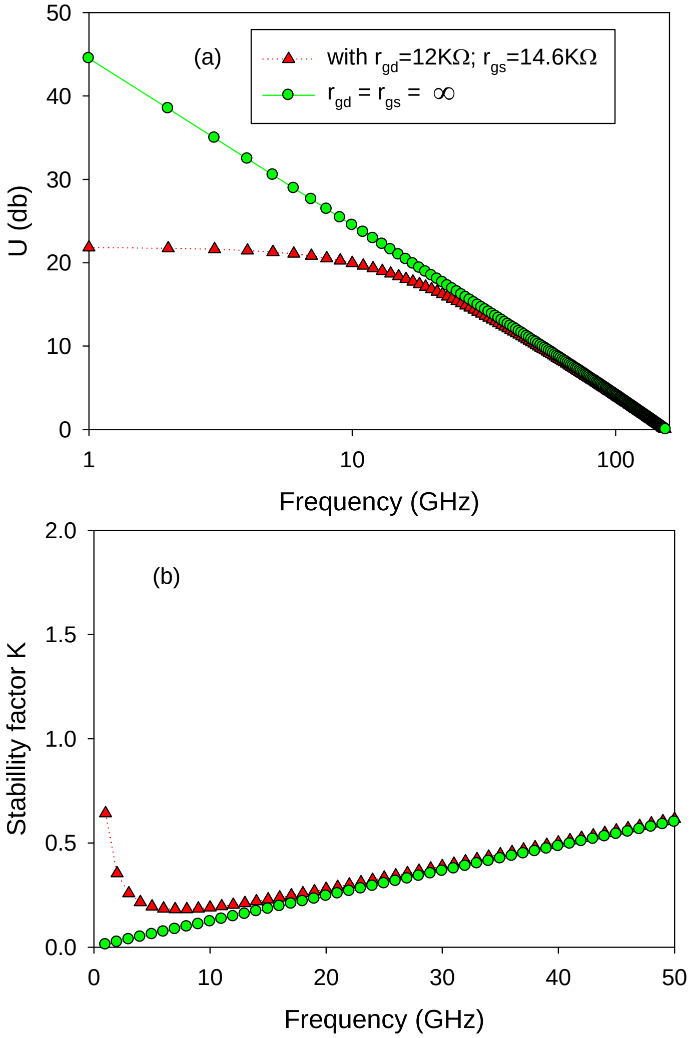

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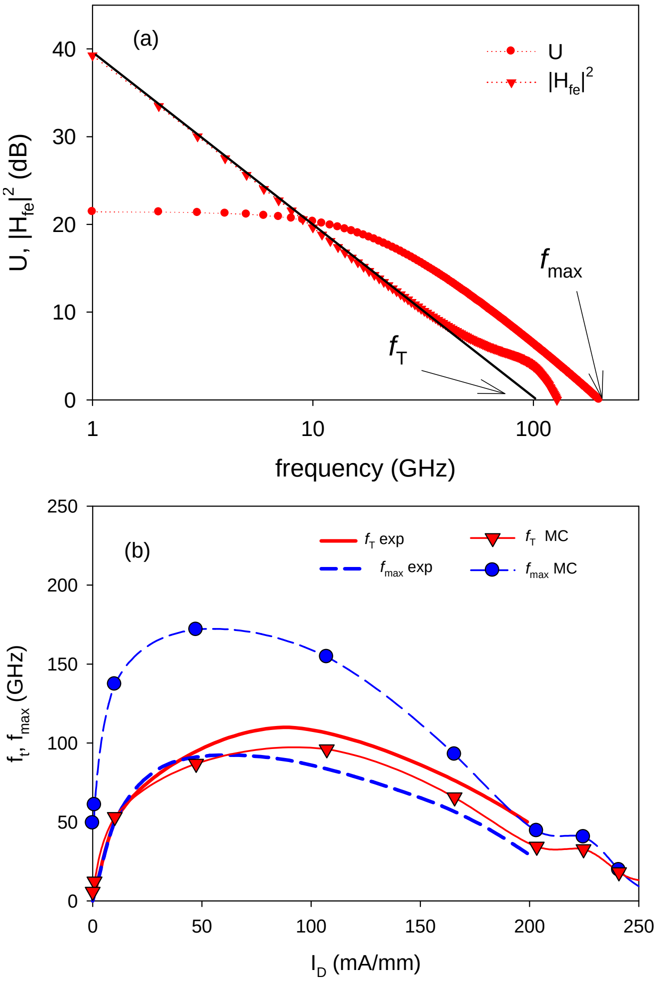

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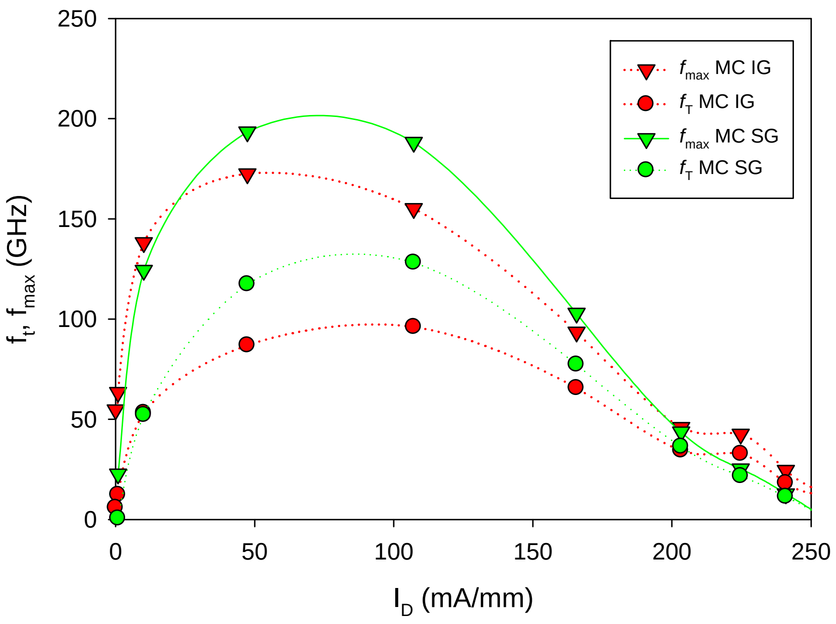

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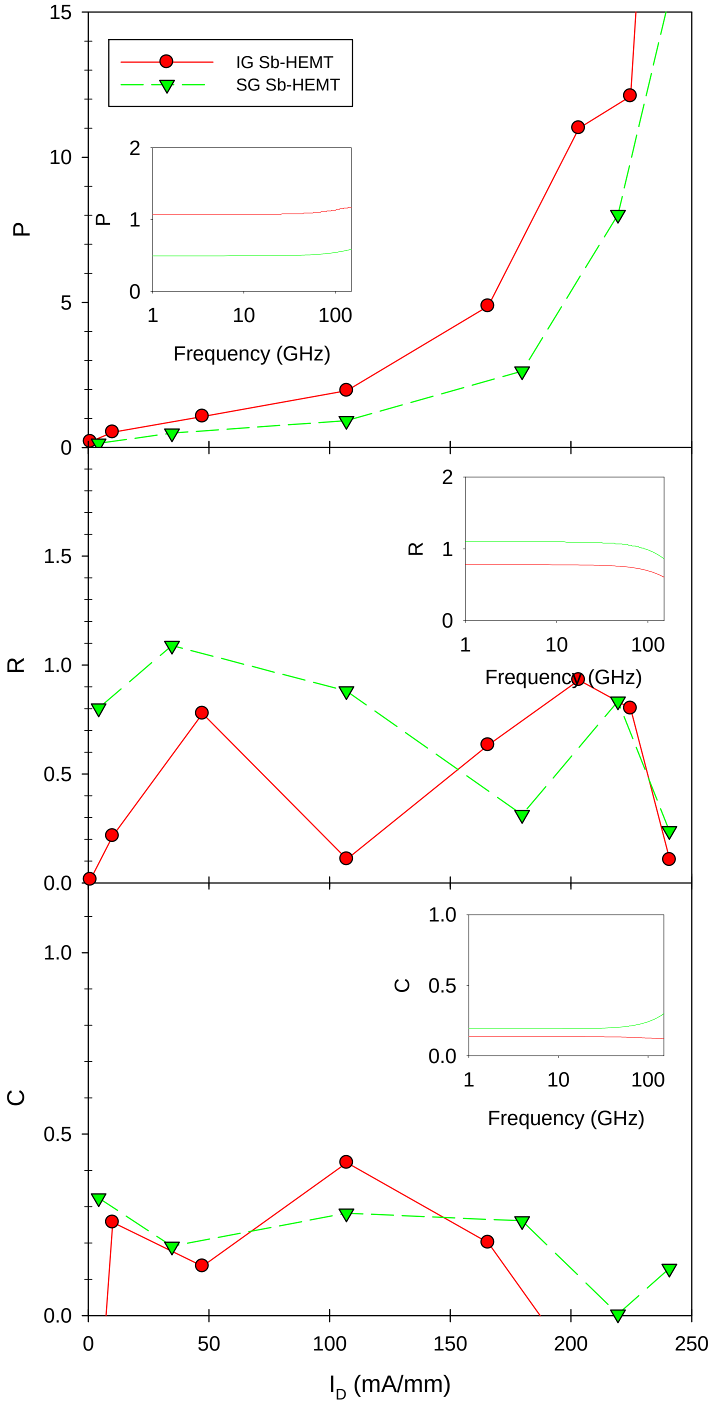

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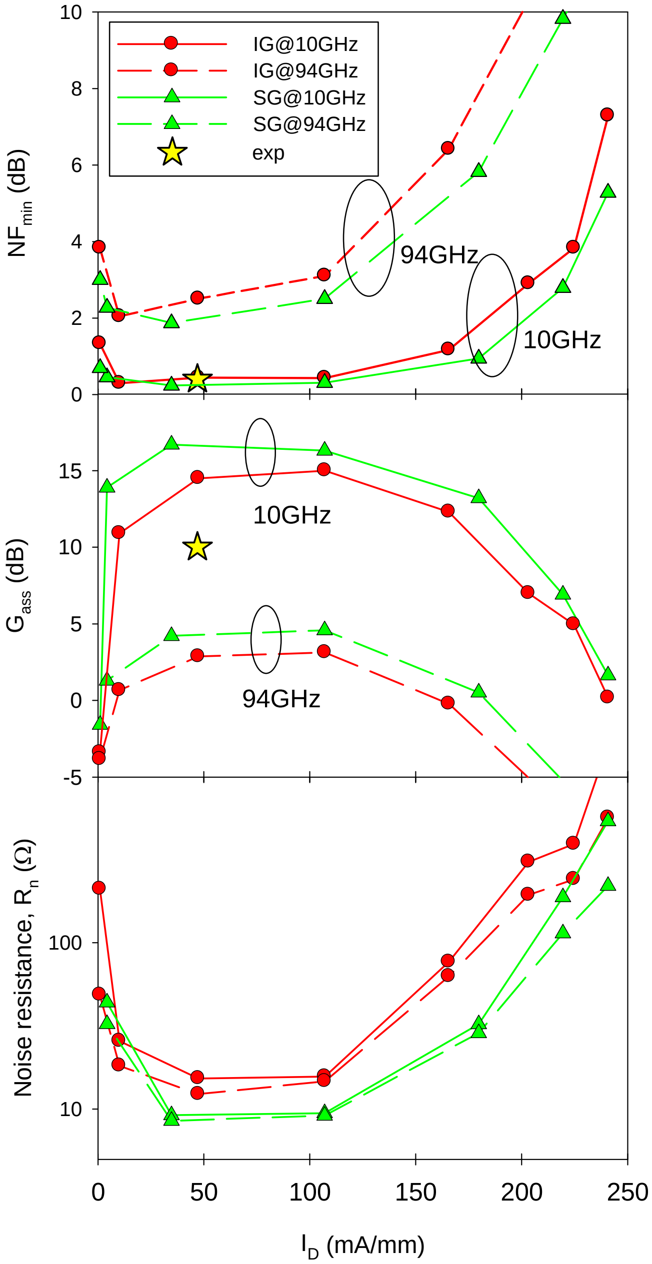

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