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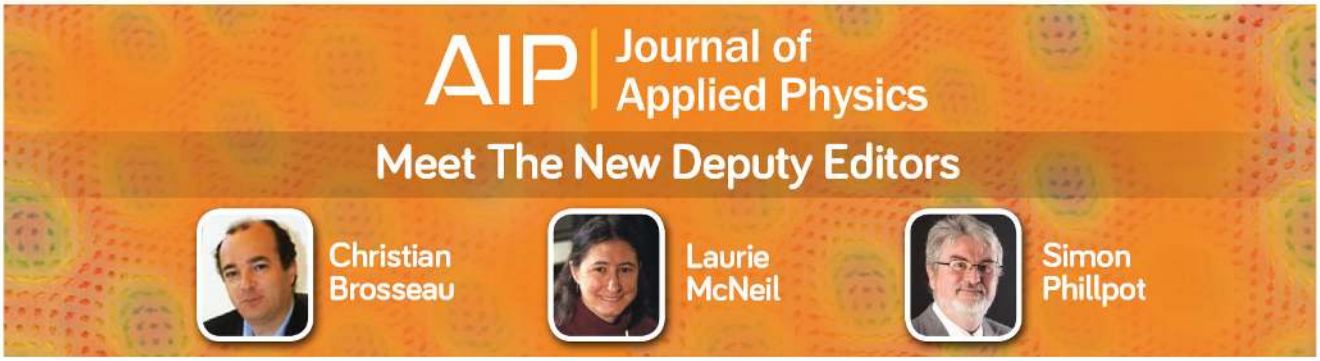

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Effect of gate leakage current on noise properties of AlGaN/GaN field effect transistors

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The effect of the gate leakage current fluctuations on noise properties of AlGaN/GaN heterostructure field effect transistors (HFETs) has been studied in conventional HFET structures and in AlGaN/GaN metal-oxide-semiconductor heterostructure field effect transistors (MOS-HFETs). The comparison of the noise properties of conventional AlGaN/GaN HFETs and AlGaN/GaN MOS-HFETs fabricated on the same wafer, allowed us to estimate the contribution of the gate current noise to the HFET's output noise. The effect of the gate current fluctuations on output noise properties of HFETs depends on the level of noise in the AlGaN/GaN HFETs. For the transistors with a relatively high magnitude of the Hooge parameter $\alpha \sim 10^{-3}$, even a relatively large leakage current I_g ($I_g/I_d \sim 10^{-3}-10^{-2}$, where I_d is the drain current) does not contribute much to the output noise. In HFETs with a relatively small values of α ($\alpha \sim 10^{-5}-10^{-4}$), the contribution of the leakage current to output noise can be significant even at $I_g/I_d \sim 10^{-4}-10^{-3}$. For such transistors, a very rapid increase of the $1/f$ noise with gate bias was observed. The differences in the noise behavior can be linked to the material quality of the AlGaN and GaN layers in different types of HFETs. © *2000 American Institute of Physics.* [S0021-8979(00)08823-X]

I. INTRODUCTION

AlGaN/GaN heterostructure field effect transistors (HFETs) have an excellent potential for high power, high frequency, and low noise applications.

Low frequency noise is one of the most important characteristics of HFETs, and the noise has to be low in the entire range of the operation gate biases. In several articles, a substantial increase of the relative spectral noise density of drain current fluctuations in AlGaN/GaN HFETs with gate voltage increase has been reported.[1–3] One of the possible reasons for the dependence of low frequency noise on gate bias is the contribution of the gate leakage current noise to the output noise.[4,5]

In this article, the contribution of the gate leakage current fluctuations to the output drain current noise of AlGaN/GaN HFETs was studied by three different methods. First, we studied the low frequency noise properties of the AlGaN/GaN HFETs and metal-oxide-semiconductor heterostructure field effect transistors (MOS-HFETs) fabricated on the same wafer under identical conditions. The MOS-HFETs had an extremely low gate leakage current and the difference in gate current between HFETs and MOS-HFETs was several orders of magnitude. Second, the gate current fluctuations were measured directly in AlGaN/GaN HFETs. The appropriate analysis of the results also allowed us to calculate the contribution of gate current fluctuations to the output noise. Third, the correlation between the gate and drain current fluctuations was measured and analyzed.

II. EXPERIMENTAL DETAILS

AlGaN/GaN heterostructures were grown by low pressure metalorganic chemical vapor deposition at 1000 °C and 76 Torr.

The first set of the structures was grown on insulating 4H–SiC. A 0.4 μm insulating GaN layer and a 50 nm *n*-GaN layer with an estimated doping level between 2×10^{17} and $5\times10^{17}\,\mathrm{cm}^{-3}$ follow a 50 nm AlN buffer. The heterostructures were capped with a 30 nm $Al_{0.2}Ga_{0.8}N$ barrier layer, which was doped with silicon approximately to $2\times10^{18}\,\mathrm{cm}^{-3}$. The measured room temperature Hall mobility and sheet carrier concentration were 1150 $\mathrm{cm}^2/\mathrm{V\,s}$ and $1.2\times10^{13}\,\mathrm{cm}^{-2}$, respectively. Prior to the transistor fabrication, a 7 nm SiO_2 layer was deposited on a part of the heterostructure using plasma enhanced chemical vapor deposition. The MOS-HFETs were fabricated on the oxidized part of the wafer. The conventional HFETs were fabricated on the nonoxidized part of the same wafer under identical conditions. The transistors had a source-drain spacing of 5 μm and a gate

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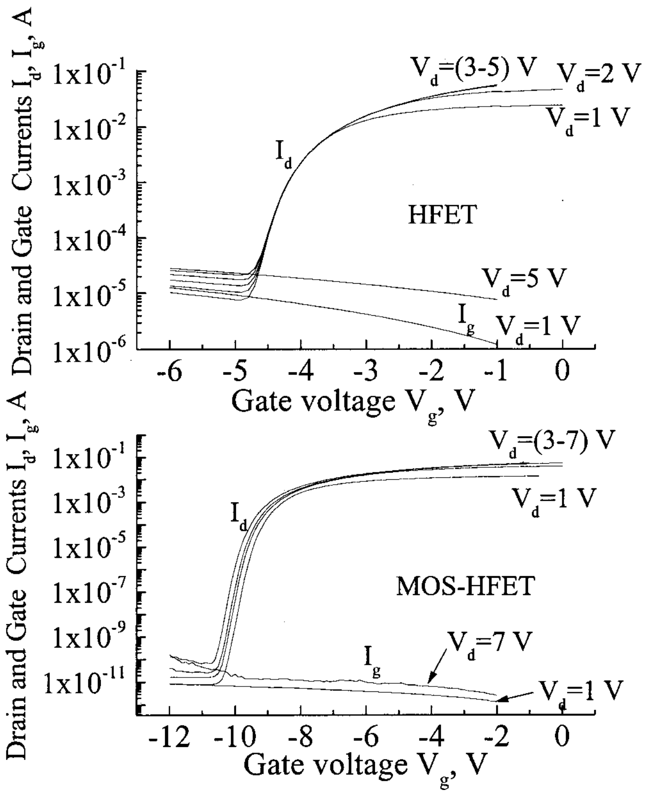

FIG. 1. Transfer characteristics and gate leakage current in HFETs and MOS-HFETs on insulating 4H–SiC substrate.

length, L, of 2 μm, and a gate width, W, in the range of 150–250 μm. More details of the structure fabrication can be found in Ref. 6.

The second set of the structures was grown on conducting 6H–SiC. The deposition of the 150 nm AlN layer was followed by the 1 μm undoped GaN layer and 50 nm n-GaN layer with the same doping level as structures from the first set. The heterostructures were capped with a 40 nm $\mathrm{Al_{0.2}Ga_{0.8}N}$ barrier layer. The measured room temperature Hall mobility and sheet carrier concentration were 1400 $\mathrm{cm^2/V\,s}$ and $1.5\times10^{13}\,\mathrm{cm^{-3}}$, respectively. Just like the transistors from the first set, these transistors had a source-drain spacing of 5 μm, a gate length, L, of 2 μm, and a gate width, W, in the range of 150–250 μm. Helium ion implantation was used to isolate devices. More details of the structure fabrication can be found in Ref. 7.

A low frequency noise was measured in the frequency range from 1 Hz to 100 kHz at small values of the source-drain bias V_{ds} (linear, unsaturated regime) with source grounded. The probe station with the tungsten probes of 10 μm diameter, and controlled pressure on the probes provided the contacts to the sample pads.

III. RESULTS AND DISCUSSION

Figure 1 shows transfer current voltage characteristics of the transistors HFETs and MOS-HFETs fabricated on the same wafer under identical conditions on insulating 4H–SiC. The dependencies of the absolute value of the gate leakage current I_g on gate voltage are also shown. In order to analyze the role of the gate current in noise properties the HFETs with relatively high current I_g were chosen. It is seen that the gate leakage current in MOS-HFETs is several orders of magnitude less than in HFETs. The extremely low current I_g in MOS-HFETs allows us to obtain more than eight orders of magnitude dynamical range of the drain current as compared with three-to-four orders of magnitude for the HFETs. At subthreshold gate voltages ($V_g \leqslant -4.5$ V for the HFETs and $V_g \leqslant -10$ V for the MOS-HFETs), the drain current is nearly equal to the gate current I_g. Hence the contribution of the gate current noise S_{Ig} to drain current fluctuations is the largest in this voltage regime. The ratio I_g/I_d decreases very rapidly with the gate voltage increase, and the contribution of the gate current to the drain current should decrease, as well.

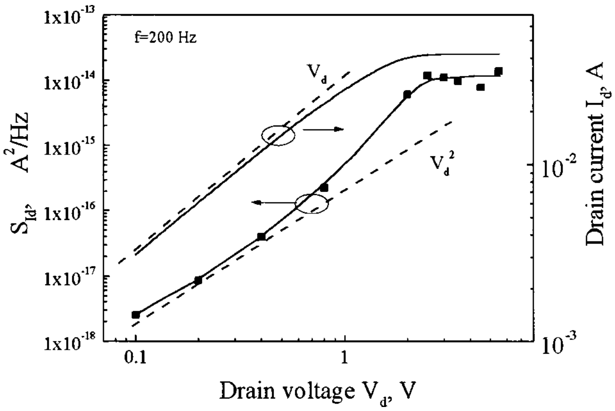

FIG. 2. Dependencies of the drain current I_d and the drain current spectral noise density S_{Id} for the HFETs. ($V_g=-2$ V).

The dependence of the gate leakage current, I_g, on the gate voltage V_g for the structures of the AlGaN/GaN HFETs on a conducting 6H–SiC substrate, were presented in Ref. 2. For the experiments described in this article, we chose the structures with the $I_d(V_g)$ dependencies similar to those shown in Fig. 1 for HFETs.

In order to determine a possible contribution of the gate current to the output noise at different gate biases we compared the noise gate voltage dependencies for the MOS-HFETs and HFETs.

The noise spectra S_{Id}/I_d^2 have the form of $1/f^{\Gamma}$ noise with Γ close to unity ($\Gamma=1.0$–1.15) for both HFETs and MOS-HFETs on insulating 4H–SiC substrates, and for the conducting SiC substrates. At low drain biases, $V_d<1$ V, the spectral noise density of drain current fluctuations S_{Id} was proportional to the square of the drain voltage $S_{Id}\sim V_d^2$ (Fig. 2). Close to the saturation S_{Id} increases somewhat faster and saturates at approximately the same drain voltage as the drain current. In the saturation region, the noise is nearly independent of the drain bias, see Fig. 2.

Figure 3 shows the dependencies of the relative spectral noise density S_{Id}/I_d^2 on drain current for several HFETs and MOS-HFETs at constant drain voltage $V_d=0.5$ V. For the devices from the first set of structures (on 4H–SiC insulating substrates) at high drain current ($V_g=0$), the values of S_{Id}/I_d^2 are almost the same for both HFETs and MOS-HFETs. The noise level corresponded to the Hooge

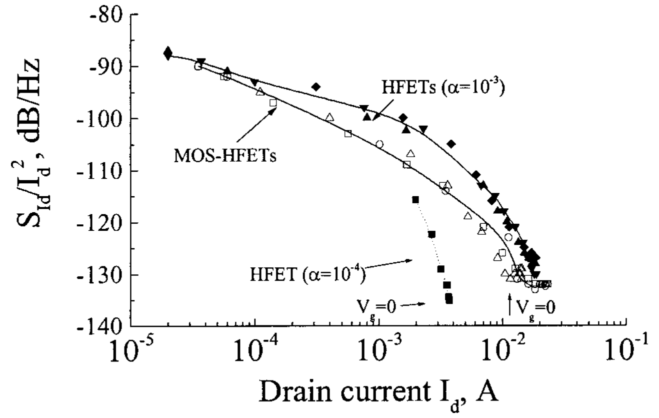

FIG. 3. Dependencies of the relative spectral noise density of drain current fluctuations S_{Id}/I_d^2 on drain current at constant drain voltage $V_d=0.5$ V for the structures with high ($\alpha=10^{-3}$, 4H–SiC insulating substrates) and low ($\alpha=10^{-4}$, 6H–SiC conducting substrates) $1/f$ noise. Frequency of analysis $f=200$ Hz.

parameter[8] $\alpha=(S_{Id}/I_d^2)Nf\approx 10^{-3}$ (here N is the total number of carriers in the channel between the drain and source). With a current decrease (i.e., at more negative gate voltages, V_g), the spectral noise density increased fairly rapidly for both the HFETs and MOS-HFETs. The difference in noise level between these two types of transistors increased with a decrease of the drain current and reached 7–8 dB at $I_d\approx 2\times 10^{-3}$ A. However, this difference cannot be explained by the contribution of the gate leakage current to the noise in HFETs. Indeed, the ratio I_g/I_d increases with a decreasing gate bias. Hence, the lower the drain current, the higher the difference between noise in HFETs and MOS-HFETs should be. However at $I_d<10^{-3}$ A, this difference becomes smaller, and at $I_d\sim 10^{-4}$ A, the noise is practically the same for the HFETs and MOS-HFETs. So, one can conclude that gate leakage current does not contribute to the output noise in the devices with the relatively high level of $1/f$ noise ($\alpha=10^{-3}$).

Structures from the second set (conducting 6H–SiC substrate) were characterized by a low level of $1/f$ noise, which corresponded to the Hooge parameter $\alpha=10^{-4}$. For these structures, spectral noise density S_{Id}/I_d^2 sharply increased with a drain current decrease (see the dashed line in Fig. 3). When the drain current decreased by a factor of less than 2, the noise spectral density S_I/I_d^2 increased by 20 dB for these devices. At the same time, for the high noise level devices, the noise increased by only 12 dB when the current changed from 2×10^{-2} to 10^{-2} A.

A rapid increase in noise was accompanied by a gate leakage current I_g.[2] Hence, one can assume that in these HFETs, the gate current fluctuations contribute to the output noise.

At small drain current $I_d<0.002$ A (large negative gate voltage), the transistors from the second set demonstrated unstable noise spectra which were not reproducible. Such a behavior can be considered as an additional evidence that the gate leakage current fluctuations contribute to the output noise.

To confirm these conclusions, the direct measurements of the gate current fluctuations have been performed.

The gate current is divided between drain and source in proportion, which depends on the gate-source and gate-drain biases and source and drain series resistances. The part of the gate current flowing to the drain gives an additive contribution to the output noise. The part of the gate current flowing to the source produces voltage fluctuations, which are amplified by the transistor.

In order to measure the gate current fluctuations, a small resistor R_g should be connected in series with the gate. If the entire gate current flows to the drain, the relative spectral noise density of drain current fluctuations due to the gate current fluctuations is given by

$$\frac{S_{Id}}{I_d^2}=\frac{S_{Vg}}{R_g^2 I_d^2}, \tag{1}$$

where S_{Vg} is spectral noise density of gate voltage fluctuations.

If the entire gate current flows to the source, it produces the voltage fluctuations across source series contact resistance R_c and across a fraction of the channel resistance, R_{ch}. This resistance is on the order of $R_c+\beta R_{\mathrm{ch}}$, where β is a parameter that depends on the gate current and is on the order of 0.2–0.5. In the linear regime, this resistance is close to half of the output resistance $r=V_d/I_d$. Hence, the fluctuations of the drain current due to this mechanism can be estimated as

$$\frac{S_{Id}}{I_d^2}=\frac{S_{Vg}}{R_g^2 I_d^2}\frac{r^2}{4}g^2, \tag{2}$$

where g is the external transconductance in the linear region.

Figure 4 illustrates the possible contribution of gate current fluctuations to the output noise of the structures with a relatively high level of $1/f$ noise (4H–SiC insulating substrate) and structures with low $1/f$ noise (6H–SiC conducting substrate). Curves labeled 1 in Figs. 4(a) and 4(b) show the measured dependencies of the drain current fluctuations S_{Id}/I_d^2 on the drain current. Symbols on curves 2 and 3 represent the contribution of the gate current fluctuations to the output noise for this structure calculated according to Eqs. (1) and (2), respectively, using the experimental values of S_{Vg}, r, and g.

Eqs. (1) and (2) represent the upper bound for these two mechanisms of the gate leakage current contribution to noise. Therefore Fig. 4(a) shows that in the HFETs with a relatively high level of $1/f$ noise, the gate leakage current fluctuations do not contribute much to the output noise.

As shown in Fig. 4(b), fluctuations of gate current can cause the output noise in the low noise devices (on conducting 6H–SiC structures). The transistors on both insulating and conducting SiC had the gate leakage current of the same order of magnitude. However, the value of Hooge constant α for these devices differed by approximately one order of magnitude.

If the gate current fluctuations cause the HFETs output noise, drain and gate current fluctuations should be correlated.

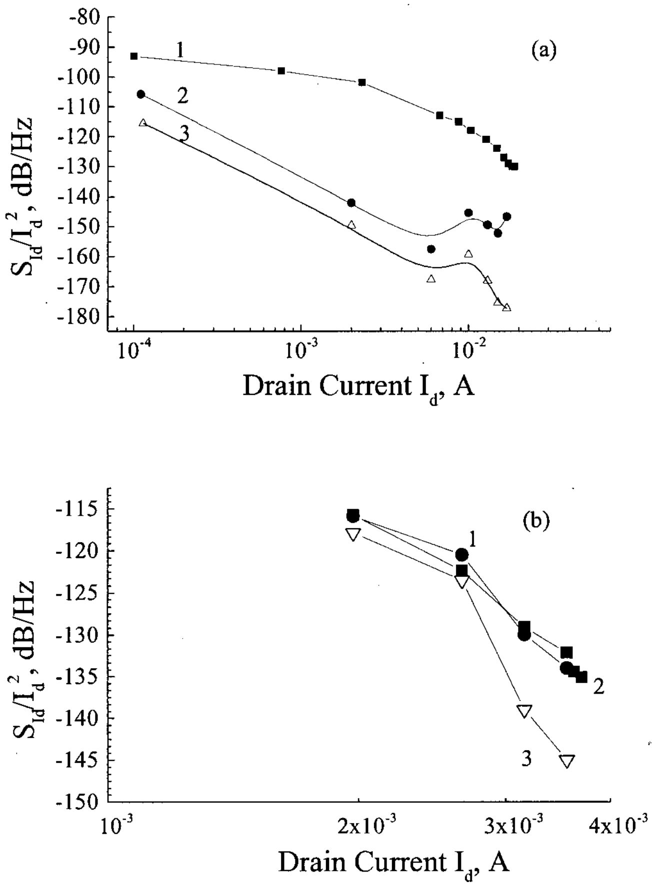

FIG. 4. Dependencies of the relative spectral noise density of drain current fluctuations S_{Id}/I_d^2 on drain current at constant drain voltage $V_d = 0.5$ V. Frequency of analysis $f = 200$ Hz. (a) High noise HFETs, (b) low noise HFETs. Curves marked with 1 represent the experimental results. Symbols on the curves 2 and 3 represent the contribution of the gate current fluctuations to the output noise calculated according to Eqs. (1) and (2), respectively.

In order to measure the cross spectrum of gate and drain current fluctuations, the signals from the drain and gate resistors were fed to the two inputs of a differential amplifier, which produced either the sum $\delta V_{\rm sum} = (\delta V_g + \delta V_d)$ or the difference $\delta V_{\rm diff} = (\delta V_g - \delta V_d)$ of these signals. The spectral noise densities $S_{\rm sum}$ and $S_{\rm diff}$ were then measured using the SR 770 Network Analyzer. The cross spectrum $S_{\rm gd}$ and the correlation function γ can be found as

$$S_{\rm gd} = \frac{S_{\rm sum} - S_{\rm diff}}{4}, \tag{3}$$

$$\gamma = \frac{S_{\rm gd}}{\sqrt{S_{Vd}} \times \sqrt{S_{Vg}}}. \tag{4}$$

The external gate resistor, R_g, (connected in series with the gate) causes an additional correlation between gate and source current fluctuations, since the gate current fluctuations are transferred to the gate voltage fluctuations and, therefore, are amplified by the transistor

$$S_{Vd} = S_{Ig} \left(\frac{R_d r}{R_d + r} \right)^2 R_g^2 g^2, \tag{5}$$

where R_d is the resistance connected in series with the drain.

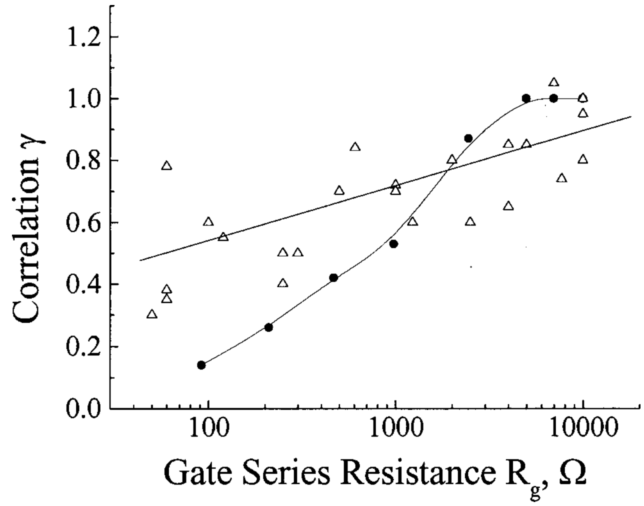

FIG. 5. Dependencies of the correlation function γ on the external gate series resistance R_g for HFETs from two different sets of wafers. Circles represent data for high noise HFETs, triangles represent data for low noise HFETs. Frequency of analysis $f = 200$ Hz. $V_g = -4$ V.

If resistance R_g is high enough, the noise signals from the gate and drain should be fully correlated ($\gamma = 1$). Figure 5 shows the dependencies of γ vs R_g for two samples from ''low'' (conducting 6H–SiC substrate) and ''high'' (4H–SiC insulating substrate) noise HFETs (triangles and circles, respectively).

For the ''high noise'' HFETs, the correlation function γ is close to unity at $R_g = 10^4\,\Omega$ and goes to zero with the decrease of resistance R_g. This proves once again that fluctuations of the gate current in these transistors do not contribute to the drain current fluctuations.

In principle, the low frequency noise in these transistors might be dominated by the contributions from the contacts, surface, and device channel. However, the increase of the relative spectral noise density S_{Id}/I_d^2 with drain current decrease indicates that the contacts and source-gate, gate-drain lateral regions do not contribute much to the noise. The dominant noise sources should be located in the device channel.[9,10]

In contrast, for ''low noise'' HFETs, γ remains fairly high ($\gamma = 0.4 - 0.8$) even as R_g approaches zero. We note that the dispersion between experimental points for these HFETs is quite large. One of the possible reasons for this phenomenon is a nonstationary behavior of the gate current, demonstrated for Si metal-oxide-semiconductor field effect transistors.[11] Hence, we conclude that in these HFETs, the fluctuations of the gate leakage current do significantly contribute to the output noise.

The difference in the noise behavior of two types of HFETs can be explained by the difference in the structural perfection of the AlGaN and GaN layers in different types of HFETs.[12]

IV. CONCLUSIONS

Our results show that in the GaN-based HFETs with a low $1/f$ noise, the gate current fluctuations can significantly contribute to the output noise. In the devices with a relatively high level of the $1/f$ noise, the contribution of the gate leakage current to the low frequency noise of drain current is fully masked by other noise mechanisms. Hence, we conclude that GaN MOS-HFETs with a high degree of structural perfection might potentially lead to the development of the transistors with ultralow $1/f$ noise, since in these devices, the gate leakage current is suppressed by many orders of magnitude.

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