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Low frequency noise of ZnO based metal-semiconductor field-effect transistors

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The low frequency noise of metal-semiconductor field-effect transistors (MESFETs) based on ZnO:Mg thin films grown by pulsed laser deposition on a-plane sapphire was investigated. In order to distinguish between noise generation in the bulk channel material, at the semiconductor surface, and at the gate/channel interface, ohmic ZnO channels without gate were investigated in detail, especially concerning the dependency of the noise on geometrical variations. The experiments suggest that the dominating 1/*f* noise in the frequency range below 1 kHz is generated within the bulk channel material, both for bare ZnO channels and MESFETs. *© 2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4906292]

Many variations of transistors based on ZnO and related materials have been presented.[1] Possible applications are often seen in the field of transparent electronics. Some proposed applications include gas sensors, due to chemically active interfaces of oxide semiconductors like ZnO. Especially for sensor applications, not only the signal transduction but also the noise generated by the device is decisive for the performance.

An early report on noise in ZnO based samples was published in 1967 by Anderson and van Vliet,[2] who examined current fluctuations in rod-like single crystals, which exhibited a 1/*f* noise spectrum between 1 Hz and 100 kHz. In the 1980s, investigations on the conduction mechanisms and noise in ZnO varistors emerged.[3,4] Below 1 kHz, the noise showed again 1/*f* characteristics. It was argued that the noise is connected to the back-to-back Schottky barriers between the ZnO grains and arises due to mobility fluctuations, as described by Hooge *et al.*,[5] but no further conclusions on the microscopic origin were drawn. More recently, investigations on ZnO thin films were reported. Often the results are difficult to compare, due to different substrates and growth techniques, which lead to varying structural and electronic properties. Also the analyses of the measured current or voltage fluctuations are not always comparable. A common way to describe a power spectral density (PSD) with 1/*f* dependence is the empirical relation

$$\frac{S_V}{V^2} = \frac{S_I}{I^2} = \frac{\alpha_H}{Nf} \tag{1}$$

proposed by Hooge.[6] S_V denotes the PSD for voltage fluctuations, S_I for current fluctuations. The Hooge constant α_H is an empirical value and N is the total number of free charge carriers. N is given by the product of the volume V_0 and the charge carrier density n, when the noise is generated in the bulk of the material. It should be noted that α_H can depend on the carrier mobility μ, either because both are dependent on the crystal quality or because the noise is directly generated by mobility fluctuations.[5] Thus, it would be desirable to find both n and μ values besides α_H in published works on low frequency noise, in order to facilitate the assessment, whether samples used for noise measurements are comparable or not. Unfortunately, this is mostly not the case. Chang *et al.*[7] investigated MBE grown films on a-sapphire. For thin films annealed at 700 °C, the 1/*f* noise below 100 Hz was characterized by $\alpha_H = 2 \times 10^{-3}$. Measurements on sputtered ZnO thin films demonstrated that an increasing growth temperature leads to a decreasing noise level.[8,9] This was attributed to the improved crystal quality. Few reports on low frequency noise in transistors based on ZnO and related materials can be found. Examples are thin film transistors based on amorphous InGaZnO (Ref. 10) and on polycrystalline ZnO.[11] The values for α_H were in the range from 0.1 to 2, determined for the complete transistor structures. As metal-insulator field-effect transistors are generally sensitive to noise generated at the insulator/channel interface,[12] the noise level actually generated in the channel material is not clear.

For this paper, pulsed laser deposition (PLD) grown thin films on a-plane sapphire were investigated, using a ZnO target with 0.25 wt. % MgO in the target. The use of this composition was reported to increase the long term stability of devices compared to binary ZnO.[13] A high concentration of aluminum donors must be expected in the thin films, provided by indiffusion from the substrate during growth. A secondary neutral mass spectrometry profile of a ZnO thin film, which illustrated this mechanism, was presented by von Wenckstern *et al.*[14] The diffusion profile of the Al donors in the film can also explain the decreasing charge carrier density of the films with increasing thickness. The films were grown at an oxygen pressure of 0.02 mbar and a substrate temperature of 650 °C. The layer thickness *a* was determined by spectroscopic ellipsometry. Mobility and charge carrier density were determined by Hall effect measurements.

In order to separate gate induced noise from channel noise, samples without gate were investigated. These samples consisted of mesa structures with varying width and

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length defined by wet chemical etching of the ZnO layer. Ohmic gold contacts were fabricated by dc magnetron sputtering.

The current noise was measured with a self-built battery-powered preamplifier and a TiePie Handyscope HS3 oscilloscope. The amplifier and the sample were placed in a grounded aluminum case for shielding. The time series recorded by the oscilloscope were used to calculate the noise PSD using autocorrelation and Fourier transformation. In order to get reasonably smooth graphs, all measurements were repeated 100 times. The average of the resulting PSD spectra was used for further analysis. By using metal film resistors as test samples, the noise of the setup was characterized for different sample resistances. The amplifier cutoff frequency was observed at 20 kHz, which causes the decreasing signal strength in Figs. 1 and 4 for frequencies above 10 kHz. It was found that the amplifier noise cannot be neglected compared to the thermal noise of the samples, but is well described by an expression based on the manufacturer's op-amp noise specifications and the thermal noise of the built-in resistors. For input resistances between 10 kΩ and 100 kΩ, the magnitude of the amplifier noise at 1 kHz is between 90% and 150% of the respective thermal noise, which is given by $S_I = 4kT/R$.

Fig. 1 shows the current noise PSD S_I of a ZnO mesa for different bias voltages. At zero bias, Nyquist-Johnson or thermal noise was observed.[15,16] The resistance $R_{\text{fit}} = 87\,\text{k}\Omega$ obtained by fitting the noise measurement was in good agreement to the resistance $R_{\text{mm}} = 84\,\text{k}\Omega$ measured by multimeter. A similar agreement was found for all investigated channels. For non-zero bias voltages higher than 0.1 V, 1/*f* noise was the dominant contribution below 1 kHz. Between 1 kHz and 10 kHz the slope of the PSD decreases, to an extent that cannot be explained solely by the transition between 1/*f* noise and the constant thermal noise. However, as the amplifier cutoff becomes effective in this frequency range, further examination of the PSD above 1 kHz is difficult. In the following, we will discuss only the 1/*f* contribution. As depicted by the inset of Fig. 1, the 1/*f* noise has a quadratic dependence on the bias voltage. Thus, the measurement series can be described by Eq. (1). By investigating ZnO channels with different geometries, the $1/V_0$ dependency of S_I was verified. Fig. 2 shows α_H values for ZnO channels with varying width, length, and thin film thickness. For the determination of each α_H value, measurements for different bias voltages were fitted simultaneously. Hall effect measurements on the films with 17 nm and 27 nm thickness yielded $n = 4 \times 10^{18}\,\text{cm}^{-3}$. The Hall mobility was $4\,\text{cm}^2/\text{V s}$ and $10\,\text{cm}^2/\text{V s}$, respectively. For the thin film with 71 nm thickness, a large difference between the sheet conductivity before lithographic structuring, determined by Hall effect, and after the patterning, obtained by *I-V* measurements, was observed. Thus, the charge carrier density $n = 8 \times 10^{17}\,\text{cm}^{-3}$ was determined by *C-V* measurements after structuring. For this purpose, we prepared Schottky diodes from Epotek H20E conducting glue, which gives sufficiently rectifying contacts on ZnO due to the high silver content. The carrier mobility was estimated using the carrier density and the measured resistivity, yielding about $70\,\text{cm}^2/\text{V s}$. All α_H values have the same order of magnitude close to 10^{-3}, except one outlier with a 100 times higher value. The reason for this deviation could not be clarified.

Metal-semiconductor field-effect transistors (MESFETs) were fabricated similarly to the channels investigated beforehand, with the addition of a Schottky barrier gate contact between the ohmic source and drain contacts. We used reactively sputtered platinum contacts, whose fabrication has been described elsewhere in detail.[13,17] The total channel length L is now divided into three parts, which are depicted in Fig. 3: The actual transistor with gate length L_G and the channel parts between gate and ohmic contacts with length L_S, acting as series resistance.

The drain current noise PSD obtained for a MESFETs at source-gate voltage $V_{GS} = 0\,\text{V}$ is depicted in Fig. 4. Thermal noise is observed for zero drain-source voltage V_{DS}. For $V_{DS} > 0$, 1/*f* noise is the dominating low frequency contribution. The inset in Fig. 4 illustrates that S_I is not dependent on I^2 for the transistor. This is due to the fact, that the transistor is a non-ohmic device. The source-drain current is limited

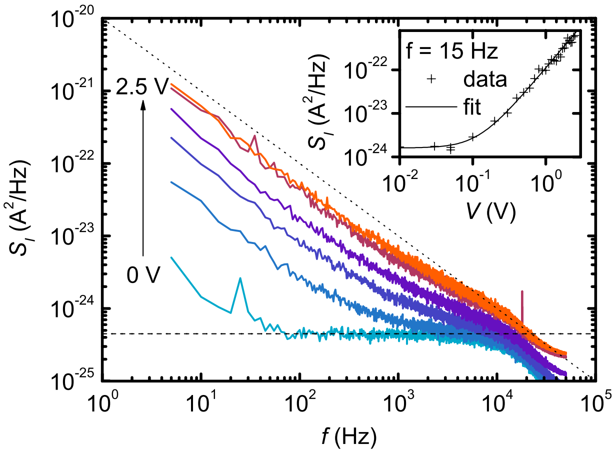

FIG. 1. Current noise PSD of a ZnO mesa structure for different bias voltages, in steps of 0.5 V. The dotted line depicts a 1/*f* dependency. The dashed line is the calculated thermal noise, including amplifier contributions. The inset shows the PSD at 15 Hz in dependence on the bias voltage. The data are fitted by the sum of a constant and a quadratic term.

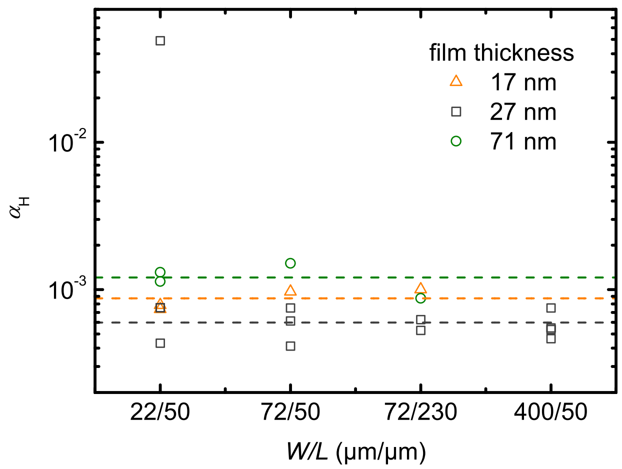

FIG. 2. Hooge constants for ZnO mesa structures with different dimensions. The mean values are 1.2×10^{-3} (71 nm), 0.60×10^{-3} (27 nm), and 0.87×10^{-3} (17 nm). The outlier for 27 nm was not included in the respective mean value.

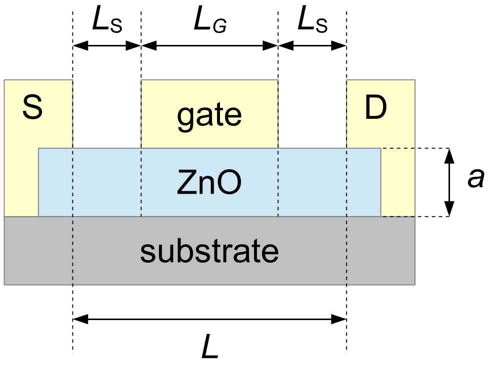

FIG. 3. Schematic cross section of ZnO MESFETs used in this study.

mostly by the part of the channel, where the depletion layer has the largest extension. It can be expected that the total current noise will depend more strongly on the noise generated in this region than on the noise contributions from the remaining channel parts. For a correct description of the noise, the contributions must be integrated along the channel. This has been done for generation-recombination noise in field-effect transistors.[18,19] The methods used in these papers can be directly applied to 1/*f* noise. This does not change the integral involved but only constants and the frequency dependency. The resulting equation is

$$S_I = \frac{e\mu V_{\mathrm{DS}} I_{\mathrm{D}}}{L^2}\,\frac{\alpha_{\mathrm{H}}}{f}. \tag{2}$$

The α_{H} constants in Eqs. (1) and (2) are directly comparable. It must be noted that Eq. (2) is only valid in the linear regime of the FET's output characteristic. In saturation, V_{DS} must be exchanged by $V_{\mathrm{DS,sat}} = V_{\mathrm{GS}} - V_{\mathrm{T}}$, where V_{T} is the transistor's threshold voltage, usually a negative voltage. According to van Vliet and Hiatt[19] also the effective gate length changes in saturation. However, due to the very high L/a ratios used in this work we can neglect this effect. In Fig. 5, we depict the PSD at 15 Hz for MESFETs having different geometry. The solid lines are calculations based on Eq. (2), each performed separately for linear and saturation regime. For all FETs, the same α_{H} value of 1.5×10^{-3} was used, in order to show that the theory yields the right order of magnitude for S_I independent of the channel geometry. Additionally, V_{DS} in Eq. (2) was corrected by the voltage drop across the series resistances, which is given by

$$V_{\mathrm{S}} = R_{\mathrm{S}} I_{\mathrm{D}} = \frac{L_{\mathrm{S}}}{en\mu W a} I_{\mathrm{D}} \tag{3}$$

for the resistance at each ohmic contact. This is especially important for the correct description of the linear regime and the transition point between the two regimes. The resulting formulas are

$$S_I = \frac{e\mu (V_{\mathrm{DS}} - 2V_{\mathrm{S}}) I_{\mathrm{D}}}{L^2}\,\frac{\alpha_{\mathrm{H}}}{f} \tag{4}$$

and in the saturation regime

$$S_{I,\mathrm{sat}} = \frac{e\mu (V_{\mathrm{GS}} - V_{\mathrm{T}} - V_{\mathrm{S}}) I_{\mathrm{D}}}{L^2}\,\frac{\alpha_{\mathrm{H}}}{f}. \tag{5}$$

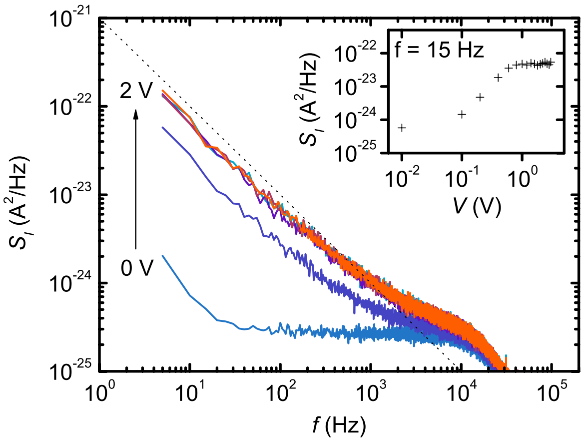

FIG. 4. PSD of the drain current noise measured on ZnO MESFETs for different drain-source voltages. The dotted line depicts a 1/*f* dependency. The gate-source voltage was 0 V. The inset shows the PSD at 15 Hz in dependence on V_{DS}.

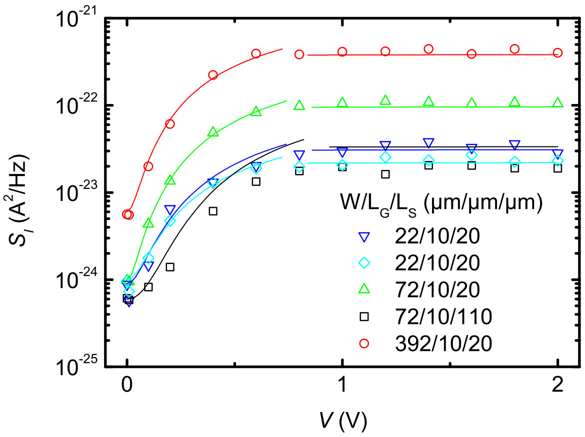

FIG. 5. PSD at 15 Hz of the MESFET drain current noise measured on ZnO MESFETs. The gate-source voltage was 0 V. The solid lines are calculations using $\alpha_{\mathrm{H}} = 1.5 \times 10^{-3}$.

These equations describe the current noise generated by the channel material below the gate, as if measured directly at the edge of the gate. Thus, noise generated by the series resistances is neglected. Also the serial connection of gated channel and series resistances is not considered, which decreases the individual contributions to the total current noise. For the devices with $L_{\mathrm{S}} = 20\,\mu$m, the fraction $V_{\mathrm{S}}/V_{\mathrm{DS}}$ is in the order of a few percent in the saturation regime. Hence, the approximation is justified. For the device with $L_{\mathrm{S}} = 110\,\mu$m, depicted by the black symbols in Fig. 5, a more significant part of V_{DS} drops across the series resistance, which explains the deviation of the calculations from measurement. Nevertheless, for sufficiently low R_{S}, the drain current noise is well described by Eqs. (4) and (5).

Current noise generated in PLD grown ZnO thin films with thicknesses between 17 nm and 71 nm was investigated. At low frequencies, 1/*f* noise prevailed for all samples with $\alpha_{\mathrm{H}} \approx 10^{-3}$. The α_{H} values deviated by a factor of maximum 3. No significant dependency on geometrical parameters was evident. Hooge[20] states that a spread of values up to an order of magnitude is often observed for nominally similar samples from different sources, and that even for measurements at different positions of one high quality GaAs sample a spread by a factor of 1.5 was observed. Thus, the values obtained for the ZnO thin films indicate that Eq. (1) is correct and $\alpha_H \approx 10^{-3}$ can be interpreted as a material constant for the films investigated. Equation (1) also implies that the 1/*f* noise originates from the bulk of the semiconductor. However, the film thickness was only varied by a factor of 4, which is not much higher than the spread of α_H values. Thus, the possibility that surface defects are involved in the generation of the observed 1/*f* noise cannot be completely excluded at this point.

The drain current noise of MESFETs based on similar thin films could also be described with a Hooge constant close to 10^{-3}. Thus, the dominating 1/*f* noise has probably the same origin in both sample types. This is a further indication for a bulk origin of 1/*f* noise in ZnO, as the ZnO surface is significantly altered by the gate deposition. Additionally, the depletion layer in the MESFETs keeps the channel current far from the gate/channel interface. An involvement of the channel/substrate interface cannot be completely excluded. A certain dependence of α_H on *a* would be expected for this case, but could be masked by the scattering of α_H values.

Several theoretical models for the origin of 1/*f* noise in semiconductors have been proposed.[5,21] However, the data on noise in ZnO are not sufficient, yet in order to decide whether mechanisms like impurity or grain boundary scattering are dominant noise sources. Clear dependencies of the measured noise on quantities like mobility, doping density, crystal quality, etc., should be available before such assignment is attempted.

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