Threshold voltage extraction method for 2D devices with power-law μ(n_S) dependence

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1. RATIONALE

Among the various methods proposed for threshold voltage extraction in 2D devices [1] the so-called ratio methods are based on the more or less linear variation vs. gate voltage of the inverse mobility: the ratio $I_{DS}/\sqrt{g_m}$ is proportional to $V_G - V_T$. It is not affected by the drain and source access resistance R_{acc}, nor by the mobility dependence on the channel carrier density [2]. However, when the linear $\mu^{-1}(V_G)$ law doesn't hold, this procedure doesn't work any more [3].

On the other hand, mobility varying with a power-law behavior as a function of the channel carrier concentration, i.e. $\mu \propto n_S^{\alpha}$ or equivalently $\mu_n \propto (V_G - V_T - V_{DS}/2)^{\alpha}$, has been evidenced in various types of devices: III-V material based devices such as AlGaAs/GaInAs/GaAs pseudomorphic HEMT [4], low density GaN/AlGaN/GaN heterostructures [5] or high-mobility InSb/InAlSb heterostructures [6], polycrystalline silicon based Thin-Film-Transistors (TFT) [7], or organic transistors such as oligothiophene TFT [8]. For these materials, the exponent α was found to vary between 0.2 and 1. In III-V devices, this behavior is limited to moderate carrier densities, and generally breaks down for $n_S \geq 10^{12}\text{cm}^{-2}$.

2. PURPOSE OF THE WORK

• We derive here a new simple and robust ratio method that provides a precise determination of the threshold voltage for device types with power-law $\mu_n(n_S)$ variation in some gate bias range above threshold.
• We show a full set of experimental results obtained in pHEMT transistors, as well as pHEMT-like gated Hall devices. The threshold value and the exponent α experimentally obtained by the new method in transistors are the same as the ones obtained from Hall measurements in gated Hall devices, where $n_{SH}(V_G) \propto (V_G - V_T)$.

3. THRESHOLD VOLTAGE EXTRACTION

Starting from the expression of the I_{DS} current when the access resistances are taken into account [9],

$$I_{DS} = \frac{W}{L_G} \cdot \mu_n \cdot C_A \cdot \left(V_G - V_T - \frac{V_{DS}}{2}\right) \cdot V_{DS} \Bigg/ \left[1 + 2 \cdot \frac{W}{L_G} \cdot \mu_n \cdot C_A \cdot R_{acc} \cdot \left(V_G - V_T - \frac{V_{DS}}{2}\right)\right] \quad (1)$$

and the $\mu_n \propto n_S^{\alpha}$ dependence, one can calculate the overall resistance $R = V_{DS}/I_{DS}$. Denoting by prime (') the derivation wrt. gate voltage V_G, it is easy to show that the ratio R'/R'' depends on V_G in a linear way:
$\frac{-R'}{R''} = \frac{1}{2+\alpha} \cdot \left(V_G - V_T - \frac{V_{DS}}{2}\right)$, where the ratio can be obtained from 3 consecutive points: $\left.\frac{-R'}{R''}\right|_n = \frac{2(R_{n-1} - R_{n+1})\Delta V_G}{R_{n+1} - 2R_n + R_{n-1}}$.

One could argue that this expression is involving a 2nd-derivative, and would thus be unsuitable for standard characterization conditions. As a matter of fact, all the experimental data shown here were measured with standard lab equipment either using a probe tester or packaged devices; noise is not an issue. Moreover, we show here that one can get a precise determination of V_T from only a few $I_{DS}(V_G)$ measurement points spaced apart by ΔV_G amounting to several 100's mV. This method has nothing in common with the so-called 2nd-derivative method.

3. EXPERIMENTAL RESULTS

Several series of pHEMT AlGaAs/InGaAs transistors with different cap layer thickness were fabricated and characterized [10], as well as gated cross-shaped devices suited for Hall measurements (Fig.1b). The power-law behavior of μ_n vs. n_S was checked (Fig.1) as well as the linear behavior of n_S vs. V_G (Fig.2). In Figs.3-5, V_T provided by the –R'/R" ratio corresponds to the threshold $n_{SH}(V_G) \propto (V_G - V_T)$, whereas the standard $I_{DS}/\sqrt{g_m}$ doesn't provide any clear threshold value. A few $I_{DS}(V_G)$ measurement points are sufficient for determining V_T (Fig.6).

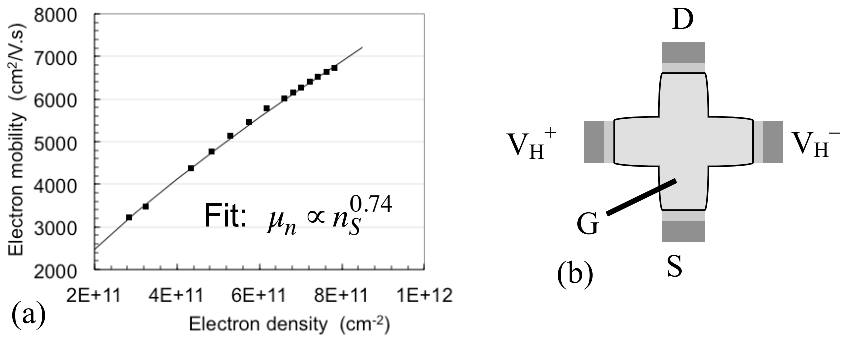

Fig.1. Mobility dependence (a) on n_S in a Hall cross-shaped AlGaAs/InGaAs/GaAs pHEMT (b) with a gate all over the channel. The mobility shows a power-law dependence on the electron density, with exponent a=0.74.

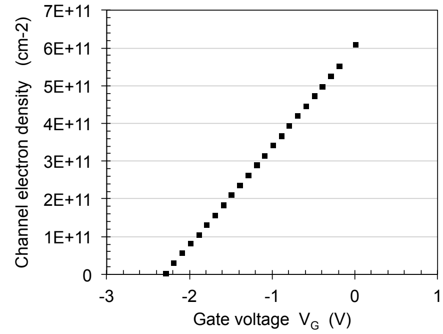

Fig.2. Experimental dependence of the Hall electron density in a Hall cross-shaped pHEMT-like Hall device. The cap layer thickness is 250nm. n_S increases proportionally to V_G increase, unambiguously defining a threshold voltage V_T.

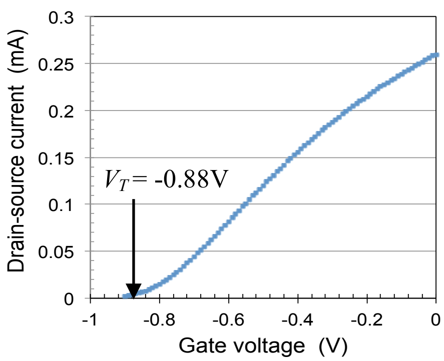

Fig.3. $I_{DS}(V_G)$ characteristics of a jumbo pHEMT transistor with 2 μm gate length and 100nm cap layer thickness.

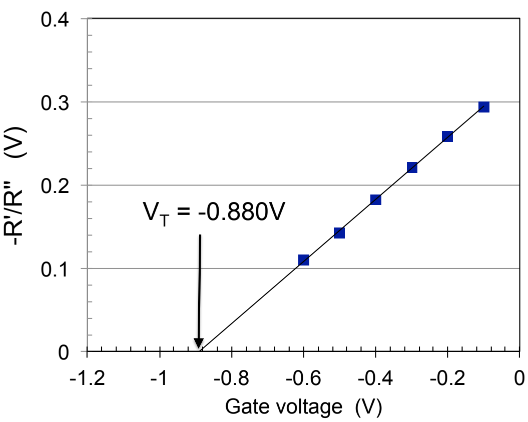

Fig.4. Ratio $-R'/R''$ calculated from the data of Fig.3, for ΔV_G=100 mV. The ratio shows a linear dependence on V_G-V_T. The threshold voltage is very close to that determined by Hall measurements in companion Hall devices. The exponent as determined from $-R'/R''=(V_G-V_T)/(2+\alpha)$, is α=0.68, close to the value determined in Fig.1.

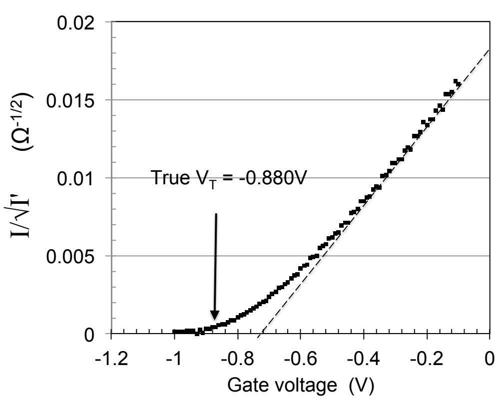

Fig.5. Standard $I_{DS}/\sqrt{g_m}$ ratio method applied to the data of Fig.3. The curvature of the curve renders the extraction of a threshold voltage difficult. The intercept of the dashed curve is more than 150mV apart from the true threshold voltage.

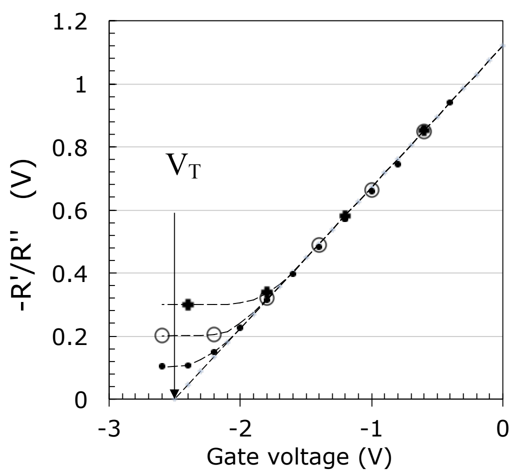

Fig.6. Ratio $-R'/R''$ for a transistor with large cap layer (258 nm), calculated for different values of the V_G increment. ΔV_G is respectively equal to 0.2 (small dots), 0.4 (large hollow dots) and 0.6V (thick crosses). The curves show a linear dependence on V_G-V_T for large enough V_G, and an asymptotic behavior $-R'/R''$ → ΔV_G /2 below and around V_T. The dashed curves are a guide for the eye.

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