Specific HEMTs for deep cryogenic high-impedance ultra low
low-frequency noise read-out electronics

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Abstract. For decades, high-impedance and low-frequency readout electronics with the lowest
noise level is based on silicon JFETs (Junction Field-Effect Transistors) with an equivalent
input noise voltage level of about 1 nV/Hz$^{1/2}$ at 1 kHz. But their operating temperature is
limited to be higher than 100 K due to their intrinsic structure. It is well known that HEMTs
(High Electron Mobility Transistors) are intrinsically available for very low temperature
operation, but conventional HEMTs suffer high gate leakage current and large channel low-
frequency noise under cryogenic condition. In order to overcome these two major issues, we
have extensively investigated the conventional HEMTs at 4.2 K by the bias-cooling method. At
a given working point, the dependence of the channel low-frequency noise on the gate leakage
current has been found out and this has allowed us to devise a new transistor structure. Specific
AlGaAs/GaAs HEMTs have then been fabricated. At 4.2 K, our HEMTs can attain a noise
level lower than 0.8 nV/Hz$^{1/2}$ at 1 kHz with an intrinsic gain $A_{int}$ of 26 and an input gate-source
capacitance of 46 pF, and their gate leakage current can be limited about 1 pA. This result
shows that our specific HEMTs may be a suitable transistor for future ultra-low noise deep
cryogenic high-impedance and low-frequency readout electronics.

1. Introduction
Cryogenic devices are designed and well used in many different fields [1,2]. And, most of them are
concerned about the cryogenic detectors and their signal amplification at very low temperatures, so
that high performance cryo-preamplifiers with very stringent signal-to-noise ratio are urgently needed
[1,2]. For decades, high-impedance and low-frequency readout electronics with the lowest noise level
is based on silicon JFETs (Junction Field-Effect Transistors) with an equivalent input voltage noise of
about 1 nV/Hz$^{1/2}$ at 1 kHz [3]. But their operating temperature is limited to be higher than 100 K due
to their intrinsic structure. The high electron mobility transistors (HEMTs) based on AlGaAs/GaAs 2
dimensional electron gas (2DEG) are naturally promising for the cryogenic application on the high-
impedance and low-frequency readout electronics, due to their special advantages [4-6]. Therefore, it
is of great interest to clarify the origin of their low frequency noise (LFN). Recently, the bias-cooling
method has been used to investigate the random telegraph noise (RTN) in AlGaAs/GaAs 2DEG QPCs
devices and from a microscopic approach RTN is considered as a source of the g-r noise and 1/f noise
[7]. After the sample is cooled from 300 K to 4.2 K with a positive (negative) gate bias $V_{ge}$, because
more (less) electrons are frozen as the DX centers in the doping area, the gate bias $V_{ge}$ for a same drain
current/bias ($I_{ds}/V_{ds}$) working point shifts to positive (negative) at 4.2 K. And, the RTN at 4.2 K can be
suppressed for the positive $V_{ge}$ cases [7].

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In this work, in Section 2, by the bias-cooling method, from a macroscopic approach, the dependence of the LFN on the gate leakage current $I_{gs}$ in the HEMT at 4.2 K has been investigated. The LFN increases with the increase of $|I_{gs}|$ at the same chosen working point (i.e. same drain bias $V_{ds}$ and drain current $I_{ds}$). The mechanism of the LFN is elucidated [8]. In Section 3, the specific AlGaAs/GaAs heterojunction is used for the fabrication of the HEMTs. For these special designed HEMTs, $I_{gs}$ is suppressed, so the LFN is suppressed. At 4.2 K, our specific HEMTs can attain a equivalent input noise voltage level $e_{n, in}$ lower than 1 nV/Hz$^{1/2}$ at 1k Hz with a high intrinsic gain, a low source-gate capacitance, and low gate leakage current.

2. Dependence of channel low frequency noise and gate leakage current in conventional HEMTs

2.1. Structure of the conventional HEMTs

The conventional HEMTs are fabricated using a Si $\delta$-doping AlGaAs/GaAs heterojunction grown by molecular beam epitaxy. The structure of the AlGaAs/GaAs heterojunction consist of, a 20 nm Al$_{0.37}$Ga$_{0.63}$As spacer layer on the GaAs buffer layer, a Si $\delta$-doping layer with the dopant density of 1.1$\times$10$^{11}$ cm$^{-2}$, a 15 nm Al$_{0.37}$Ga$_{0.63}$As barrier layer, and a 5 nm GaAs cap layer. The AlGaAs/GaAs interface for 2DEG is 40 nm underneath the surface. At 4.2K, the carrier concentration of the 2DEG is 4.9$\times$10$^{11}$ cm$^{-2}$ and its mobility is 2.8$\times$10$^5$ cm$^2$/Vs. The gate length is 16 $\mu$m and width is 1.89 mm. Before the metallic deposition of the Schottky gate, about 1 nm GaAs cap layer has been etched.

2.2. Measurement results

![Figure 1. $I_{ds}$-$V_{gs}$ curves (Solid lines) with $V_{ds}$ = 100 mV for the $V_{gc}$ cases of -100 mV (Black), 0 mV (Green), and 100 mV (Red), respectively. The circular symbols indicate the points of $I_{ds}$ = 1 mA $V_{ds}$=100 mV at $V_{gs}$ = -293, -208 and -113 mV, respectively. $I_{ds}$-$V_{ds}$ curves (Dashed lines) at these three different $V_{gs}$ for the upper three $V_{gc}$ cases, respectively.](image)

The HEMTs are cooled from 300 K to 4.2 K with an applied gate bias $V_{gc}$ from -120 to 150 mV. Fig. 1 shows $I_{ds}$ vs. $V_{gs}$ at the drain bias $V_{ds}$ = 100 mV for the cases of $V_{gc}$ = -100, 0 100 mV at 4.2 K. For the more negative (positive) $V_{gc}$ case, the $I_{ds}$-$V_{gs}$ curve clearly shifts to more (less) negative $V_{gs}$, but keeps the same shape. The working point for the noise measurements is chosen as $I_{ds}$ = 1 mA and $V_{ds}$=100 mV. For the different $V_{gc}$ cases, at the respective $V_{gs}$ for the chosen working point, Fig. 1 also shows $I_{ds}$ vs. $V_{gs}$. And, the $I_{ds}$-$V_{ds}$ curves are identical, independent of $V_{gc}$. Thus, the transistor characteristics for an amplifier, i.e. the transconductance $g_{m}$ and the output conductance $g_{d}$, remain the same. For the different $V_{gs}$ cases, $V_{gs}$ for the chosen working point and the corresponding $|I_{gs}|$ are shown in the Fig. 2a. Those $V_{gs}$ data are almost linear to $V_{gc}$. $|I_{gs}|$ is as small as the measurement limit.
for the cases of $V_{gc} \geq 50$ mV, and increases almost exponentially with the decrease of $V_{gc}$ for $V_{gc} \leq 25$ mV.

The noise measurement setup is shown as the inset of Fig. 2b, where the load resistance $R_L$ is 301 $\Omega$. The channel voltage power spectra density (PSD) $S_V$ is measured by a vector signal analyzer from 50 to 100k Hz. The noise current PSD $S_I$ is deduced from $S_I = S_V / R_c^2 - 4k_B T R_c$, where $R_c = R_g / (R_g + 1)$ is the effective output resistance, $k_B$ is the Boltzmann constant, and $T$ is the temperature. $S_I$ vs. the frequency $f$ at the chosen working point for the cases of $V_{gc} = -100$, -50, 0, 50, 100, and 150 mV are shown in Fig. 2b. For the cases of $V_{gc} = 50$, 100, and 150 mV, $S_I$ curves are almost same, and they show the typical $1/f$ noise shape with $S_I \propto 1/f^\alpha$ and $0.9 < \alpha < 1$. For the cases of $V_{gc} \leq 0$ mV, the curves show $S_I \propto 1/f^\alpha$ with $\alpha \approx 1.65$ in the high frequency regime, and $S_I$ is higher for the more negative $V_{gc}$ cases. For these cases, the g-r noises appear and more g-r noises are added into the LFN for the more negative $V_{gc}$ cases.

Figure 2a. $V_{gs}$-$V_{gc}$ relationship for the chosen working point $I_{ds} = 1$ mA and $V_{gs} = 100$ mV, the experimental results (circular symbols) are in agreement with the simulation (line). $|I_{gs}|$ for the cases of $V_{ge}$ from -120 to 150 mV is shown by the square symbols.

Figure 2b. $S_I$ vs. $f$ from 50 to 100k Hz at the chosen working point for the different $V_{ge}$ cases. The upper dashed line is proportional to $1/f^{1.65}$ and the lower one is proportional to $1/f^{0.95}$. The insert shows the noise measurement setup.

2.3. Discussion

For the AlGaAs/GaAs 2DEG devices, some electrons are frozen as the meta-stable DX centers (DX-) in the doping area at about 120 K [8]. For the HEMTs at 4.2 K, because the less electrons are frozen as DX- during cooling the samples from 300 K to 4.2 K for the more negative $V_{gc}$ cases, the electron density in the 2DEG is higher and consequently, the $V_{gs}$ needed for a given electron density, and thus $I_{ds}$-$V_{gs}$, are shifted towards more negative values.

For the chosen working point, Fig. 3a shows the band diagram for a positive $V_{gc}$ case. For this kind of cases, the gate Fermi level $E_{Fg} = -e V_{gs}$ is much lower than shallow donor levels $E_d$. Only the direct-tunnelling from the gate to the 2DEG may exist, and the thickness of the heterostructure barrier for the tunnelling is that of the barrier layer plus the spacer layer, so $|I_{gs}|$ reaches our measurement limit as shown in Fig. 2a. And, the direct-tunnelling cannot produce the g-r noise [8], so $S_I$ remains at its minimal level as shown in Fig. 2b.
But, for the negative $V_{gc}$ cases, or even just the case that $V_{gc}$ is lower enough, $E_{fg}$ can be higher than $E_d$ for the chosen working point, as shown as the band diagram in Fig. 3b. When $E_{fg} > E_d$, there is not only the direct-tunnelling, but also the sequential-tunnelling from the gate to the empty levels in the doping area formed by the ionized shallow donors or the potential valley formed by the barrier layer and spacer layer (DAPV area in Fig. 3), and then to the 2DEG. For the sequential-tunnelling, the empty levels in the DAPV area may act as the g-r sites to produce the g-r noises [8]. The LFN is the sum of these g-r noises and the 1/f noise. With the decrease of $V_{gc}$, because $E_{fg}$ for the chosen working point increases, the electrons can tunnel into the higher energy empty levels in the DAPV area, so more g-r noises are summed into $S_I$. Hence, $\vert I_{gs}\vert$ increases almost exponentially with the decrease of $V_{gc}$ as shown in Fig. 2a, and $S_I$ increases as shown in Fig. 2b.

In summary, because the different amount of electrons are frozen as the meta-stable DX centers in the doping area, during the conventional AlGaAs/GaAs 2DEG HEMT cooling from 300 K to 4 K with the different gate bias $V_{gc}$, at 4.2 K, the gate bias $V_{gs}$ for a same drain current/bias ($I_{ds}/V_{ds}$) working point is different, but the main transistor characteristics, $g_m$, $g_d$, and the gain, remain the same. This means, the low frequency noise (LFN) can be observed at the chosen working point at 4.2 K, with the different $V_{gs}$ and gate leakage current $I_{gs}$. With the increase of $I_{gs}$, the LFN increases, and its increased component is the g-r noises, which is supposed to be caused by the sequential-tunnelling component of $I_{gs}$. Hence, if $I_{gs}$ is suppressed, the LFN should also be suppressed.

3. Realization of ultra low low-frequency noise in specific designed HEMTs

3.1. characteristics of the specific designed HEMTs

The specific AlGaAs/GaAs heterojunction are applied to fabricate the HEMTs in order to suppress the gate leakage current. At 4.2 K, the carrier concentration of the 2DEG is $5 \times 10^{11}$ cm$^{-2}$ and its mobility is $3.7 \times 10^5$ cm$^2$/Vs. The gate length and width are as the same as the conventional ones.

3.2. Measurement results

All measurements in this section are performed at 4.2 K. For the HEMTs, $I_{ds}$ and $I_{gs}$ vs. $V_{gs}$, and $I_{ds}$ vs. $V_{ds}$, are measured by source meters, and their gate capacitance $C$ vs. $V_{gs}$ at $V_{ds} = 0$ is measured by a
LCR meter. The source-gate capacitance $C_{gs}$ and the drain-gate capacitance $C_{gd}$ are measured by the cut-off frequency method [6,9]. The noise is measured as same as the section 2. The effective output resistance $R_e$ and the external gain $A_{ext}$ are measured by the lock-in amplifier, where $A_{ext} = g_m R_e$. The equivalent input noise voltage level $e_{in}$ is obtained by $e_{in} = \frac{V_{ref}}{A_{ext}}$.

Fig. 4a shows $I_{ds}$ and $I_{gs}$ vs. $V_{gs}$ at $V_{ds} = 10, 60$ and $100$ mV, in which $V_{gs}$ regime for the noise measurements is from -159 mV to -190 mV above the threshold. In the noise measurement regime, $|I_{gs}|$ is always less than 1.1 pA due to the specific AlGaAs/GaAs heterojunction. In this regime, the gate capacitance $C$ is almost constant at 72 pF, and $C_{gs}$ and $C_{gd}$ at $V_{ds} = 100$ mV are almost constants as $C_{gs} \approx 46$ pF and $C_{gd} \approx 4.5$ pF.

Fig. 4b shows $I_{ds}$ vs. $V_{ds}$ at $V_{gs}$ from -155 to and -190 mV, and $C_{gs}$ and $C_{gd}$ vs. $V_{ds}$ at $V_{gs} = -165$ mV. $C_{gs}$ increases from $C_{gs} \approx 35$ pF $\approx 1/2C$ at $V_{ds} = 10$ mV in the linear region to $C_{gs} \approx 46$ pF $\approx 2/3C$ in the saturation regime, and $C_{gd}$ decreases from $C_{gd} \approx 40$ pF$\approx 1/2C$ at $V_{ds} = 10$ mV to $C_{gd} < 10$ pF in the saturation regime. $C_{gs}$ and $C_{gd}$ almost keep constant in the saturation region, which is consistent with the theoretical predictions for the characteristic capacitance of an ideal FET [10].

Fig. 5a shows $e_{in}$ at 1 kHz vs. $I_{ds}$ for $V_{ds} = 100$ mV. The lowest $e_{in}$ at 1 kHz is 0.77 nV/Hz$^{1/2}$ at $I_{ds} = 0.8$ mA. The corresponding intrinsic gain $A_{int}$ vs. $I_{ds}$ is also shown in Fig. 5a, where $A_{int} = g_m g_d = A_{ext} R_e / (R_l - R_e)$. And, $A_{int} = 26$ at $I_{ds} = 0.8$ mA and $V_{ds} = 100$ mV. Fig. 5b shows the $e_{in}$ spectra at $I_{ds} = 0.8$ mA and $V_{ds} = 100$ mV, in which $e_{in}$ at 100kHz is 0.18 nV/Hz$^{1/2}$. 

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**Figure 4a.** $I_{ds}-V_{gs}$ curves (solid lines) and $I_{gs}-V_{gs}$ curves (dot lines). The noise measurement regime is between the two dashed lines, in which $|I_{gs}| < 1.1$ pA.

**Figure 4b.** $I_{ds}-V_{ds}$ curves in the noise measurement regime from $V_{gs} = -155$ to -190 mV with the step of -5 mV. $C_{gs}-V_{ds}$ plots and $C_{gd}-V_{ds}$ plots at $V_{gs} = -165$ mV.

**Figure 5a.** The plots of $e_{in}$ at 1kHz vs. $I_{ds}$ and $A_{int}-I_{ds}$ plots for the fixed $V_{ds} = 100$ mV.

**Figure 5b.** $e_{in}$ spectra at $I_{ds} = 0.8$ mA and $V_{ds} = 100$ mV.
3.3. Discussion
For the specific designed HEMTs, by the simulation, the gate Fermi level $E_{Fg}$ is found higher than the shallow donor levels $E_d$ in the working regime. But, using the specific AlGaAs/GaAs heterojunction with an additional barrier in barrier layer, at 4.2 K, the gate leakage current $I_{gs}$ is suppressed, so the LFN is suppressed. The lowest $e_{n \text{in}}$ at 1kHz of $0.77 \text{nV/Hz}^{1/2}$ at $I_{ds} = 0.8 \text{mA}$ and $V_{ds} = 100 \text{mV}$ is realized.

4. Conclusion
By the bias-cooling method, from a macroscopic approach, the dependence of the low frequency noise (LFN) on the gate leakage current $I_{gs}$ in the HEMT at 4.2 K has been investigated. The LFN increases with the increase of $|I_{gs}|$ at the same chosen working point (i.e. same drain bias $V_{ds}$ and drain current $I_{ds}$). The LFN due to $I_{gs}$ is supposed to be caused by the sequential tunnelling component of $I_{gs}$. The specific AlGaAs/GaAs heterojunction is used for the fabrication of the HEMTs. For these special designed HEMTs, $I_{gs}$ is suppressed, so the LFN is suppressed. At 4.2 K, our specific HEMTs can attain a equivalent input noise voltage level $e_{n \text{in}}$ in about $0.77 \text{nV/Hz}^{1/2}$ at 1kHz at $I_{ds} = 0.8 \text{mA}$ and $V_{ds} = 100 \text{mV}$ with the intrinsic gain $A_{int} = 26$, the source-gate capacitance $C_{gs}$ about 46 pF, the drain-gate capacitance $C_{gd}$ about 4.5 pF, and $|I_{gs}|$ about 1 pA. All these performances are as good as or even better than those of the silicon JFETs for the cryogenic preamplifier. This result shows that our specific HEMTs may be a suitable transistor for future ultra-low noise deep cryogenic high-impedance and low-frequency readout electronics [3].

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