Cryogenic Semiconductor Electronics

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The Milan group has centered its activity on cryogenic microelectronics on the use of GaAs MESFET technology. This choice was taken after having found extremely low HF noise at 4 K in discrete MESFETs fabricated by NEC and SONY about 20 years ago. Those devices have been discontinued and replaced by equivalent units which nevertheless did not give the same cryogenic performance. A commercial MESFET process has been characterized at cryogenic temperatures, after which FETs and monolithic preamplifier circuits, intended for operation in liquid Helium and liquid Argon, have been designed and fabricated. We will report on our FETs and monolithic preamplifiers which could be of interest for STJ applications. We will briefly review characteristics and results obtained with other technologies which promise new opportunities for the realization of deep cryogenic front-end electronics.

KEYWORDS: cryogenics, electronics, GaAs, noise, STJ

1. Introduction.

Signal-to-noise ratio in particle detectors using Superconducting Tunnel Junctions (STJ's) depends on the nature of the primary event, on the characteristic time constant of the junction and on the electronic noise of the preamplifier5. For direct interaction of X rays in the junction, the event is contained in a small region while in phonon detection with composite detectors, larger areas are involved. In the first case, all STJ area not contributing to the signal just adds capacitance and therefore only contributes to increase noise. In the second case there is in principle no difference in using a large area junction or a series/parallel combination leading to lower capacitance. This last option avoids need of field-effect transistors (FET's) with extremely large input capacitance, required to match the detector.

The need to keep low the contribution of noise sources related to the detector-preamplifier link, like microphonics and radio frequency interference (RFI) or the cross talk in case of multielectrodes devices, asks for transistors operating in the vicinity of the detector typically between 1 K and 4 K. For the first purpose Si JFETs self-heated to their optimum temperature (~140 K) are frequently used because those devices have the lowest HF noise and the parallel noise at optimum temperature is extremely low. An alternative solution is to count with devices capable to operate at 4 K or less, also with lowest noise. An effort in this direction has been pursued by various groups. Results will be reported in this paper with special emphasis on our own work.

In the next section we will recall the main properties of field-effect transistors when they are operated at cryogenic temperatures. In section 3 examples of GaAs based cryoelectronics designed for particle physics experiments are presented. In section 4 we briefly review characteristics and results of new technologies under investigation.

2. FET's at cryogenic temperatures.

Freeze-out of carriers in the channel sets a limit to the minimum temperature a FET could operate. For a Si JFET, it could even reach 40 K although its optimum operating temperature is in most cases close to 140 K. Si MOSFETs do compensate carrier freeze-out thanks to the strong field under the gate and are used in high density applications at 4K.

Still, MOSFETs are affected by large HF noise and DC instabilities at cryogenic temperatures. In FETs based on III-V materials freeze-out effects are much smaller, as donor ionization energy is only a few meV.30 At low temperature carriers could reach high velocities specially in the undoped channels of high electron mobility FETs (HEMFETs) for which low-field mobility can reach impressive values, Fig 1.

High electron mobility in FETs means larger transconductance gm with less power dissipation as $g_m = (W/L)\mu C_\mu$ $I_f/I_{sat}$, higher transition frequency as $\nu_T = \frac{1}{2\pi} (g_m/C_\mu) \mu L$, and low white noise as the Equivalent Noise Charge, for a matching factor $\eta = \frac{C_p}{C_g}$: $\eta = \frac{4(\pi k T \frac{V_T}{\nu_T})^2}{\alpha_{p} A_T} \frac{\nu_T}{g_m} (m^2 + m^{-2})^{1/2} \frac{C_p}{C_g} (0)$

In the equations above, $I_f/I_{sat}$ is the ratio of bias to saturation current. $W/L$ is the gate width-to-length ratio. $C_g$ is the input capacitance of the first amplifying device, and $C_p$ the detector capacitance. Parameter $\nu_T$ depends on the type of shaping used while $\nu_T$ is the peaking time. Parameter $A_T$ of eq. (1) is the factor of merit for the low frequency defined as the product of its spectral density coefficient $A_T$ times $C_p$. Low-frequency noise becomes the limiting factor in relatively slower detector systems.

GaAs FETs improve their low-frequency noise when they are cooled down. This is not the case of Si MOSFETs for which noise at 4 K could be even higher than at room temperature6.

We have found commercial dual-gated GaAs MESFETs which have surprisingly low values of HF noise at 4 K. Noise reduces still when both gates are connected together emulating a longer gate device. SONY's 3SK164 and NEC's
We have developed FETs and low noise preamplifiers in GaAs MESFET technology for applications in particle physics. For the fabrication, a commercially available process was used. An array of MESFETs (W=50 mm and L = 1, 2, 5 and 10 mm) have been manufactured and evaluated at 4 K. The factor of merit for 1/f noise was quite good $H_f = 3 \times 10^{20}$ Joule which indicated that this process could be suitable. Unfortunately, although $H_f$ was not expected to depend on device size, much larger devices fabricated later had $H_f$ values of the order of $10^{19}$ Joule.

We recall in this section the relevant properties of a few devices which could be of interest for use with STJs.

3. Large gate-area FETs.

To match detector capacitances of few hundreds picofarad, MESFETs with large gate-area have been fabricated and successfully operated at 4 K and 77 K. They have been used as discrete units or as the input stage of low-noise monolithic preamplifiers for bolometric particle detectors, at 4 K. Devices of particularly large gate-width ($W = 24000$ mm) have been used at the input stage of monolithic preamplifiers for LAr calorimetry in the frame of an R&D detector development at CERN. In this case those chips have been created at 77 K and 87 K. For bolometric detectors, devices with $W = 6000$ mm were characterized at 4 K.

To facilitate design of monolithic structures, we have accurately characterized test devices at cryogenic temperature and modeled them with SPICE parameters extracted at cryogenic temperature. Fits with models valid at room temperature are sufficiently accurate in a region around the desired operating point. Results of simulations performed with those parameters were in good agreement with experimental results.

Figure 3 shows a noise density level spectrum of a $(L \times W)$ $3 \times 6000$ $\mu m^2$ FET, biased at $I_{DSS} = 60$ mA and $V_{DS} = 0.3$ V, operating at 4 K. The coefficient of the 1/f noise spectrum is $A_f = 8 \times 10^{-14}$VHz^{-1} and the factor of merit is $H_f = 2.4 \times 10^{23}$ Joule ($C = 30$ pF).

2. Cryo FETs and monolithic circuits in GaAs

Fig. 1: Low field mobility in different FET channels as a function of operating temperature.

Fig. 2: Inset: referred noise at 4 K of a set GaAs MESFETs in parallel: SONY's 3SK164 (discontinued) and its replacement SGM2006.

Fig. 3: Inset: referred noise at 4 K of a $(L \times W)$ $3 \times 6000$ mm$^2$ GaAs MESFET measured with TanQuant's QEDA process. Power dissipation is $14.25$ mW.
3.2 Voltage Preamplifier for operation at 4 K.
Following development of large FETs, a monolithic differential voltage-preamplifier designed for operation at 4 K was fabricated. The differential structure allowed to obtain excellent common mode rejection ratio (CMRR) around 75 dB up to few kHz, Fig. 4. Noise, besides being unexpectedly high, was even higher at 4 K than at 77 K. At 10 Hz it was 190 nV/√Hz at 4 K and 250 nV/√Hz at 77 K. This behaviour was correlated to a higher resistivity of the channel compared to previous runs. Correlation between noise at cryogenic temperatures and channel resistivity was systematically verified in our various process runs.

3.3 Octal charge-sensitive preamplifier
This instrument was designed to readout the signal of a LAr shower detector, in the frame of the R&D collaboration at CERN. Fig. 5 shows a top view of the octal preamplifier chip which matches detector capacitance of about 10 pF.

Measurements of ENC versus detector capacitance and shaping time have been performed at 77 K. A fit from these measurements allows to determine that the white noise is 0.5 nV/√Hz and the 1/f noise coefficient $A_f = 2 \times 10^{-11} \text{V}^2$. Extrapolated capacitance of the input device is 12 pF. Minimum ENC is 200 electrons rms. Other relevant parameters are: power dissipation 4 mW per channel, gain-bandwidth product 1 GHz. Performance at 4 K has not been verified yet.

A plot of ENC at 77 K as a function of detector capacitance is shown in Fig. 6.

3.4 Performance of the process at cryogenic temperatures.
In order to have a better control of the electrical performance at cryogenic temperatures of the selected process, pin-off voltage and noise have been recorded and plotted against the resistivity of the channel for every process run. It was found the expected inverse correlation of the absolute value of pin-off voltage with channel resistivity, Fig. 7, and also an increase of white noise and of its temperature dependence with resistivity, Fig. 8.
Plot of Fig 8 shows the input referred white noise in the channel. It clearly shows that at lower resistivity, noise is small and is also very small the increase observed when temperature decreases from 87 K to 77 K. As transconductance remained basically constant, increase of noise translated into a larger white noise coefficient g which extended from -2 for RDS = 580 Ωsq to -10 at 77 K for RDS = 675 Ωsq. Unfortunately it was not possible to draw in advance the value of RDS in these cases, noise was higher than expected from extrapolations of previous runs. Nevertheless, the experience gained allows us to conclude that the GaAs MESFET process selected is mature for cryogenic use in medium and high frequency applications.

This process was in fact adopted for the cryogenic signal readout circuits of the Hadronic End-Cap Lar Calorimeter of the ATLAS experiment at CERN.8

![Graph](image)

Fig 8. White noise density at 77 K and 4 K. τ = 12% of FET's fabricated in various runs. It is evident a correlation between noise and its sensitivity to temperature with channel resistivity. Circles and triangles indicate different voltage.

4. New alternative processes

4.1 Heterojunction bipolar transistors (HBTs)

Standard bipolar transistors exhibit at low temperatures base freeze-out and a decrease in carrier lifetime. This translates into lower transition frequency and lower current amplification factor β. Improvement on this behaviour has been reached through better vertical profile depth and doping levels. A plot showing reduction of β at lower temperatures in different technologies is shown in Fig 9. Heterojunction bipolar transistors are considered good candidates for cryoelectronics possibly also at the lowest temperatures. Through bandgap engineering of the base, SiGe HBTs can even improve their current gain at LN temperature. Fig 9.

A corner frequency for the 1/f noise down to 100 Hz have been claimed for SiGe HBTs (13) which in addition to their low temperature operating capabilities makes it a promising technology.

![Graph](image)

Fig 9: Trends in corner gain as a function of temperature for Si-based bipolar technologies. (Source: J. Osterle)

4.2 Pseudomorphic (Al,In,Ga)As/GaAs HEMTs

High electron mobility transistors (HEMTs) have very large 1/f noise at room temperature but this noise in known to reduce when the device is cooled down. Recent reports indicate that pseudomorphic (Al,In,Ga)As/GaAs HEMTs at 4K operate in a very low current regime have a 1/f noise coefficient $A_{1/f} = 4 \times 10^{-12}$ V/Hz, a white noise less than 0.5 nV/√Hz, and a shot noise of 0.76 FA/√Hz with a power dissipation less than 10 mW. Those preliminary results confirm that the pseudomorphic HEMT have improved dynamic and noise operation at 4K.

4.3 Ge JFETs

Ge JFETs have been fabricated by Texas Instruments about 30 years ago showing high performance at 4 K. Despite the interest within the cryoelectronic research community these devices were discontinued. Recently, an initiative to fabricate Ge JFETs optimised for low noise at liquid Helium temperature has been established. Preliminary measurement on tests devices have shown that DC characteristics are good although threshold effects are present unless devices are biased in the pA regime. First noise measurements show that it is still high but optimization of materials and design could lead to substantial improvements.

5. Summary and conclusions

We have reported on the activity carried out in Milan on cryogenic electronics, pointing out those aspects that could be of interests for the Japan-Russia collaborative work on Superconducting Tunnel Junctions. We have shown that GaAs MESFETs technology could be successfully used in
applications at liquid Helium temperature specially if the lowest 1/f noise is not required, but high speed of response and low power dissipation. We have also briefly reviewed the work done by other groups on new technologies, SiGe HBTs, pseudomorphic HEMTs and Ge JFETs for deep cryogenic electronics may open new opportunities in front-end electronics for STJs.

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