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III–V FRONT–END ELECTRONICS – AN OVERVIEW

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Abstract

Characteristics of III-V devices and performance of monolithic circuits used for the readout of particle detectors are reviewed. High speed and low white noise of MESFETs and HEMFETs are accompanied by the large 1/f noise observed at room temperature in those devices. HBT's instead, have lower 1/f noise and seem to be a promising technology for many HEP applications. Complementary C-HFETs would allow realization of radiation-hard front-end and logic circuits for vertex detectors. At cryogenic temperatures, monolithic preamplifiers made with the already mature MESFET technology demonstrated extremely low noise and matching capability to read out the high capacitance cells of a LAr prototype detector.

1. - INTRODUCTION

Use of GaAs technology for the readout of particle detectors was addressed for the first time not too long ago when commercially available metal-semiconductor field-effect transistors (MESFETs) were considered for the realization of low noise front-end electronics for detectors at large hadron colliders [1, 2]. One characteristic of GaAs devices that primarily attracted investigators was the large transition frequency that those transistors exhibit. A large transition frequency translates into a lower noise at fast shaping times [3], but noise of available

MESFETs had, at room temperature, a large 1/f component that in principle limited their use to applications with shaping times at most of a few tens of ns.

Dominant 1/f noise in MESFETs was observed to decrease strongly upon cooling, which suggested their possible use with cryogenic particle detectors [4]. Those detectors are based on electrothermal principles and have been proposed for the implementation of particle physics experiments, such as neutrino-less double-beta decay, solar neutrino detection, and search for dark matter particles [5]. 1/f noise, dominant at room temperature, decreases more than two orders of magnitude in most MESFET types cooled to LHe temperature (4 K) [6, 7].

Research aiming at understanding the parameters which determine the low frequency noise in cooled MESFETs began, and a few years later cryogenic detectors could benefit from preamplifier hybrid circuits based on GaAs MESFETs and operated at 4 K [8]. Use of GaAs devices for cryogenic low noise readout circuits for spacecraft and other applications has also been reported [9-12].

The good performance obtained with MESFETs at extremely low temperatures suggested their possible use with cryogenic liquid calorimeters, where those devices showed promise to fulfill stringent detector requirements. Actually, the cryogenic liquid calorimeter under investigation [13] required fast, low-power, low-noise electronics able to operate immersed in the cryogen to reduce the charge transfer time between detector and preamplifier [14]. After developing the first charge-sensitive preamplifier based exclusively on GaAs MESFETs [15], hybrid circuits with tailored matching capacitance were designed and tested with a prototype LAr calorimeter [8, 13].

More recently MESFETs with large gate area, exhibiting series white noise of $0.2\ nV/\sqrt{Hz}$ from 77 K to about 150 K have been developed [16], and later full monolithic circuits demonstrated excellent noise and dynamic performance [17].

At present, monolithic low-noise preamplifiers made with a GaAs ion-implanted MESFET process are foreseen in ATLAS for the readout of the hadronic end-cap LAr calorimeter [18] and have been used with the electromagnetic LAr Accordion prototype calorimeter [19, 20]. Another III-V technology, complementary-heterojunction FET (C-HFET), has been suggested for liquid calorimetry [21] and some groups have investigated this alternative attracted by the high radiation resistance of a C-HFET process [22]. Characteristics of this C-HFET process at deep cryogenic temperatures have also been reported [23].

Development of GaAs detectors for tracking has motivated several groups to search for a compatible technology to match detector capacitances of a fraction of pF [24 - 26]. High electron mobility FETs (HEMFETs) are under consideration primarily because of their transition frequency which could reach a few hundred GHz [25, 27, 28]. As noted above, this parameter translates into low white series noise which could be made the dominant term if the 1/f noise could be kept under control. This seems to be possible only at very fast shaping times. HEMFET technology is nowadays readily available from several sources.

Radiation hardness was believed to be a property of GaAs devices no matter what process they were made with. Recent work has been conducted to assess the actual dynamic and noise performance in a frequency region of interest in HEP, i.e. below about 30 MHz. Results show that MESFET noise is more sensitive than Si JFETs regarding ionizing radiation, while the situation reverses when devices are subjected to neutrons. On the other hand DC characteristics are quite stable for neutron fluences up to a few times 10^{14} n/cm^2 and a total dose of 55 MRad [29, 30]. The C-HFET process showed negligible noise change for total photon dose up to 100 MRad [22].

Nowadays, GaAs front-end electronics has become competitive in certain areas in which its characteristics can not be surpassed by other approaches. For instance, applications at cryogenic temperatures, below 150 K, where noise becomes much lower compared to Si JFETs of similar capacitance; or at 4 K where 1/f noise is lower than that of MOSFETs (the only Si device able to operate at that low temperature); or when high speed/power performance and radiation resistance are required at shaping times of a few ns.

The formidable explosion of telecommunication circuits boosted the GaAs industry, once devoted mainly to military applications, and this will certainly be of benefit for our applications in the field of experimental physics.

In this paper, the most relevant properties of GaAs devices and circuits of interest for the field of particle physics are reviewed.

2. - RELEVANT DEVICE PROPERTIES

GaAs MESFETs were the first devices based on III-V materials, first introduced in the mid 60's [31], but actual devices became readily available in the 80's, about 20 years later, after Si JFETs were widely used for applications in nuclear and sub-nuclear physics [32]. MESFETs are majority carrier devices controlled by a single-sided gate electrode forming a Schottky barrier with the channel.

HEMFETs, whose principle of operation was introduced in 1978 [33], became readily available only at the end of the 80's, either as discrete devices and as a foundry process. In those devices, carriers created in a $Ga_{1-x}Al_xAs$ n^+ doped region tunnel into the undoped GaAs channel where they can reach extremely high velocities.

Pseudomorphic HEMFETs [34], in which the undoped GaAs channel was now substituted by a $Ga_{1-x}In_xAs$ layer, could reach much higher modulation efficiencies and therefore higher transition frequencies, in excess of 100 GHz.

In GaAlAs devices electron mobility in the channel is very high, in particular at low temperatures. Higher mobility translates into a high transconductance/input capacitance ratio and therefore into high transition frequency and low white noise. Fig. 1 shows a plot of electron mobilities in different devices' channels. For comparison the electron mobility in a Si JFET channel is also indicated. It can be observed that at room temperature there is no significant difference between various III-V devices (but all of them surpass Si JFET's). At LN_2 or LAr temperature (77 K and 87 K respectively), electrons in a AlGaAs HEMFET channel become much faster than in all other devices, due to lack of impurity scattering in the undoped channel.

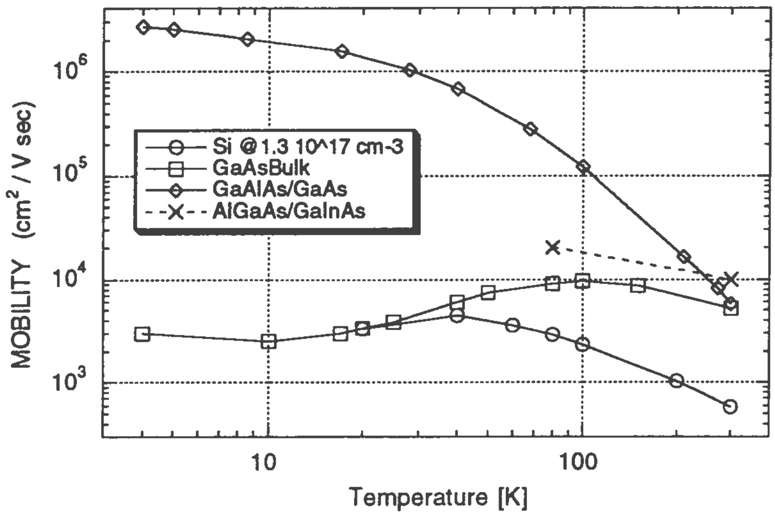

Fig 1. – Electron mobilities in FET channels at different temperatures.

In addition to III-V FETs, heterojunction bipolar transistors (HBT's) must be also taken into account for front-end realization as those devices have an extremely high transition frequency, which could reach 200 GHz [35], and low 1/f corner frequency. Corner frequencies as low as 1.6 kHz have been reported for InP based HBT's [36]. In addition HBT's have an extended temperature operating range, reaching 4 K. A new device, very competitive to III-V HBT's, is the SiGe HBT for which excellent properties in terms of transition frequency and 1/f noise at room temperature has been reported [37].

The superior transition frequency of the mentioned devices must not make us forget that in most demanding applications in particle physics the bandpass of analog signals will be centered at comparatively low frequencies. For instance, a shaper amplifier with a bipolar delta response peaking at 10 ns has a narrow bandpass centered at about 16 MHz. Low-noise preamplifiers followed by such a shaper would require about 3-4 GHz GBW product.

At this point, with high speed of response assured by III-V devices, noise becomes a prime parameter that deserves special attention. All III-V FETs exhibit 1/f noise that could dominate in the frequency region of interest. Reported work on HEMFET preamplifiers shows that 1/f noise is dominant at shaping times longer that a few tens of ns [22, 38]. Reduced 1/f noise could be obtained by optimizing the gate length and/or by optimizing the process. For example, the Glasgow group reported reducing 1/f noise in their HEMFETs by controlling dry etching [27].

As mentioned above, 1/f noise decreases by cooling. To illustrate, two noise spectra from MESFETs are shown below: In Fig. 2 the spectral density of a commercial device cooled to 4 K shows the best low-frequency noise ever reported for a single GaAs device [9, 15]. Measurements were conducted in Milano, and later the same device was measured at Stanford for comparison. The 1/f noise factor of merit introduced by V. Radeka, H_f, is defined as the product of A_f, the coefficient of 1/f spectral power density, times the input capacitance of the device, Ciss. (Other factors of merit have also been defined [39]). H_f for the NEC 41137 is

2.5 x 10^{-26} Joule. As a comparison we recall that for a low-noise Si JFET, which is the best FET regarding 1/f noise behaviour, H_f at the optimum temperature of about 150 K is about 10^{-27} Joule.

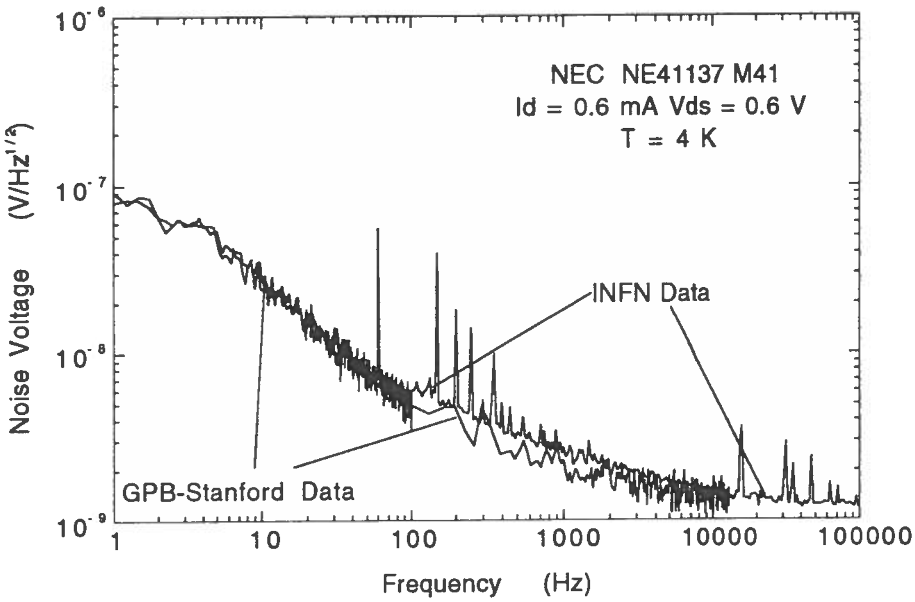

Fig. 2 – Input-referred noise of a commercial MESFET at 4 K exhibiting extremely low 1/f noise. Both Milano and Stanford/Gravity Probe B independent measurements on the same device show similar results [9].

To match detector capacitances in the range of a few hundred pF, MESFETs with large gate area have been fabricated using an ion-implant foundry process [16]. Fig. 3 shows the noise spectra of a MESFET with (Lg x Wg) 3 x 24000 μm^2. It can be observed that noise changes very little from 87 K to 150 K, that the corner frequency is about 1 MHz and that the white noise is lower than 0.2 nV/√Hz. This device is used as the input transistor of monolithic preamplifiers developed for LAr calorimetry [17].

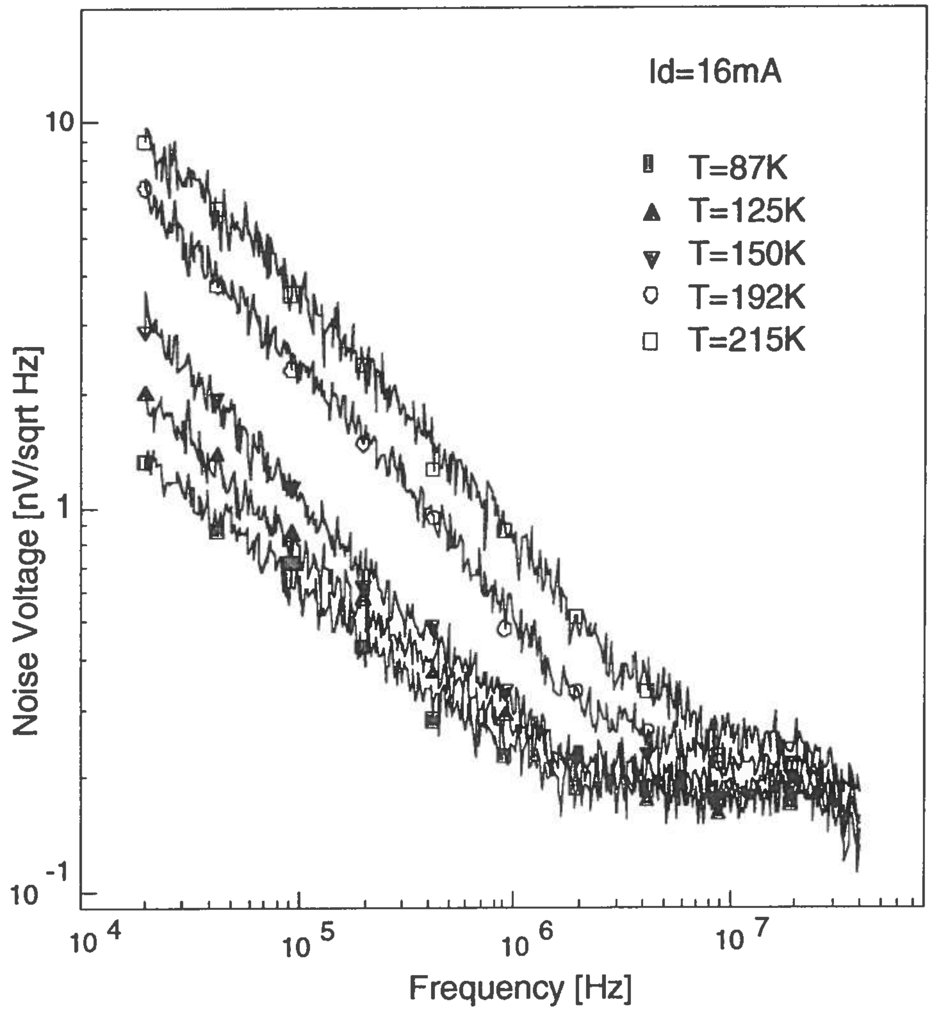

Fig. 3 – Input-referred noise for different temperatures of a 3x24000 μm^2 MESFET fabricated with an ion-implant process. With I_d=16 mA, white noise is slightly less than 0.2 nV/√Hz. The roll-off above 30 MHz is an artifact of the measurement.

3. - CIRCUITS

So far, GaAs circuits have been used in real experiments for signal readout of cryogenic detectors [5], and in LAr calorimetry [18, 19]. In those cases the operating temperature was low, and therefore the contribution of 1/f noise was either reduced or not relevant. There is also interest in using GaAs front-end electronics with particle detectors working at room temperature; however, so far no reports have been made regarding real physics results obtained with such an approach.

In this section, we show the most important results obtained with GaAs monolithic circuit designed by the Milano group and fabricated using TriQuint's QED/A process. The same process was used by the Munich group to develop the front-end electronics for the hadronic end-cap LAr calorimeter of ATLAS [18].

A dual-channel GaAs monolithic preamplifier developed for the electromagnetic LAr calorimeter of ATLAS has a GBW in the compensated mode of 1.5 GHz and the average noise level of a batch of chips is about 0.3 nV/√Hz with the best units reaching 0.2 nV√Hz. The power dissipation is 55 mW. A photograph of the die is shown in Fig. 4. This circuit was used to read out about 600 channels of the Accordion LAr calorimeter under development at CERN. During tests it was demonstrated that the electronic noise is a factor two lower than that of the other solutions proposed to read out this detector, Fig. 5. Radiation hardness to the levels expected after 10 years of operation in LHC was also demonstrated [17, 29].

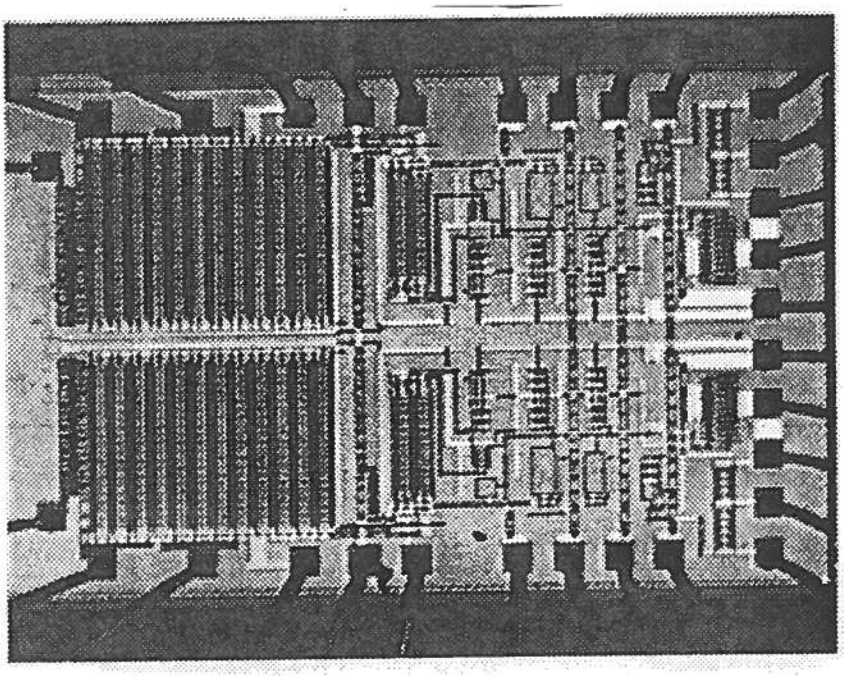

Fig. 4 – A dual-channel preamplifier for LAr calorimetry. Die size is 1.5x2.5 mm^2. Note the area occupied by the input FETs which have Lg x Wg = 3 x 24000 μm^2.

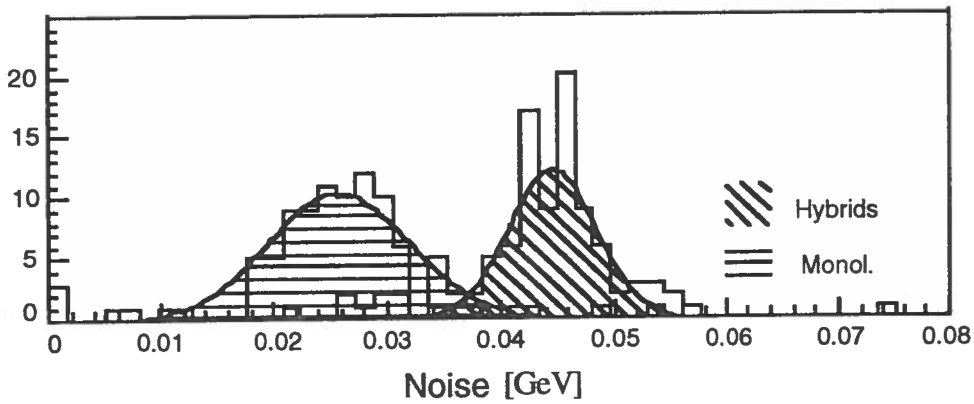

Fig. 5 – Electronic noise in the first segment of the prototype LAr electromagnetic calorimeter. Monolithic GaAs preamplifiers allowed noise reduction by ~ 50 % [20].

The reader is referred to ref. [17] and [40] for further details relative to the design and fabrication of this chip as well as radiation damage tests.

4. - CONCLUDING REMARKS

III-V devices have speed performance well in excess of what is required by most front-end electronics used with particle detectors. Very low white noise could also be achieved but 1/f noise seems to be a limiting parameter that must be controlled to expand use of the various III-V technologies above the shaping time limit of a few tens of nanoseconds at room temperature. The strong decrease of 1/f noise when a MESFET is cooled makes this technology suitable for reading out the signals from cryogenic liquid calorimeters and other cryogenic detectors. Monolithic preamplifiers using FETs with very large gate area have been developed and tested with a prototype LAr detector obtaining reduction in electronic noise by 50% compared with alternative readout solutions.

Regarding the future, III-V and SiGe HBTs, which have very low 1/f noise at room temperature, seem promising for many HEP applications. Indications of possible reduction of the 1/f noise of HEMFETs and MESFETs by acting on the fabrication process are good news. The complementary C-HFET process seems suitable for implementing very fast analog and logic ASIC's for high radiation environments.

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