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GAS LOW NOISE PREAMPLIFIERS FOR CRYOGENIC PARTICLE DETECTORS

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ABSTRACT

The use of GaAs MESFETS in the realization of low-noise preamplifiers for particle detectors is reported in this paper. Operation at cryogenic temperatures is favored by the low noise temperature of dopant impurities in the MESFET channel and by the high charge sensitivity at temperatures as low as 4K. Voltage preamplifiers for 4K operation have been developed and are used with bolometric particle detectors. Charge preamplifiers for high importance cryogenic detectors and liquid calorimeters have also been developed and are presently used for the analysis of the Accellerator Lab calorimeters prototype at CERN. A monolithic design based on a GaAs p-channel field-effect transistor has also been tested. A preliminary project based on a monolithic array of MESFETS was also tested.

1. Introduction

GaAs metal-semiconductor field-effect transistors (MESFETS) have been identified as suitable candidates for the realization of low-noise preamplifiers for cryogenic detectors as these devices exhibit, at cryogenic temperatures, good dynamic and noise performance. In effect, freeze-out of carriers is observed only at temperatures of the order of 1K, low frequency noise decreases strongly when cooling down and a large gain-bandwidth product is obtained with low power dissipation. At room temperature, instead, charge-sensitive preamplifiers using MESFETS give their maximum benefit as short shaping times when the equivalent noise charge (ENC) is limited by the white noise and the effect of the dominant 1/f noise becomes negligible. The most relevant properties of GaAs MESFETS will be reviewed, and examples of “usage”-sensitive preamplifiers used for the signal amplification of thermal detectors and charge-sensitive preamplifiers developed for fast thermal detectors and for liquid Argon calorimeters will be described. Finally, the characteristics of recently developed charge-sensitive preamplifiers based on a monolithic process will also be reported.

2. Properties of GaAs MESFETS

Nature has given GaAs fundamental physical parameters which make it an attractive option for the realization of cryogenic low noise, and fast amplifiers. In fact, the high electron mobility and low electric field for carrier peak velocity make it possible to obtain high transconductance at low power dissipation. This is a parameter of prime importance in charge-sensitive preamplifiers as it is related to the product of the charge sensitivity times the speeds for a given detector capacitance. In addition, the low ionization energy of dopant impurities keeps limited the freeze-out of carriers even at 4K.

Some fundamental parameters of GaAs are indicated in Table 1 and, to make a comparison with the well-established Si technology, the corresponding values for silicon are also given. A hoping level of 10^17 cm^-3 have been assumed in both cases.

<table>
<thead>
<tr>
<th>GaAs</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>380K</td>
<td>77K</td>
</tr>
<tr>
<td>3K</td>
<td>1K</td>
</tr>
<tr>
<td>0.7</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>1.4</td>
<td>1.1</td>
</tr>
</tbody>
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The selection of suitable MESFETS is done among those device types exhibiting low noise at low frequencies which is the main limiting parameter. Noise temperature series noise in MESFETS is mainly of generation-recombination type and dominates at low frequencies. The distribution of the spectral power density is proportional to 1/f due to the presence of multiple traps. The noise spectral power density takes the form \( \Sigma k_i (1+\omega_i^2) \) which has a dependence near a large range. At low temperatures this dominant 1/f noise source strongly due to the exponential dependence of \( \kappa_i \) with decreasing temperature. Reduction of two orders of magnitude in the spectral power-density when temperature decreases from 300 K to 7 K was observed for some n-type devices. An additional feature of first noise reduction is observed in many device types when cooling to 4 K.

To reduce the low frequency noise per unit gate-width, devices with long gate are necessary. Obviously, long gate reduces the transition frequency of the device but this might not constitute a problem in applications of relatively low frequencies. An experiment to test the gate-length dependence of 1/f noise was performed using double-gate MESFETS. Results have shown that the spectral power density scales with \( L_g^{-1} \) in noise temperature and with \( L_g^{-2} \) in noise temperature and with \( L_g^{-2} \) at LN and LHe temperature. This is consistent with the assumption that 1/f noise is of generation-recombination type at room temperatures and approaches the exponential Hooge's law at very low temperatures. The 1/f noise contribution falls away. The inverse 1/f noise dependence on the power of gate-length, of about \( L_g^{-2} \) to 4K, was recently also verified by other investigators in test devices with different gate lengths. These studies will be used to the design of devices optimized for the amplification of signals generated by cryogenic particle detectors.

Regarding what noise, it is the limiting parameter in the signal-to-noise ratio at very high frequencies or, equivalently, at short shaping times. The large transconductance-to-input capacitance ratio of GaAs MESFETS makes it possible to obtain low dependence
of the equivalent noise charge (ENC) on the detector capacitance in charge preamplifiers while keeping low the power dissipation. In effect, the ENC in matching conditions is given by:

$$\text{ENC} = \frac{kT}{\sqrt{g_{m}C_{d}}} \times \frac{1}{G} \times \frac{1}{\tau}$$

(1)

where \( k \) is about 1.28 for GaAs at 300K, \( T \) is 300K, \( g_{m} \) is the gain-bandwidth product of the input device, \( h_{r} \) is a numerical parameter dependent on the shaper considered, \( C_{d} \) is the device parasitic capacitance, \( \tau \) the measuring time and the rest are usual terms. MESFETs precisely used in cryogenic preamplifiers have \( h_{r} \) for values in excess of 1 GHz with less than 40 mV power dissipation at 77K.

Regarding radiation hardness, GaAs devices have been thoroughly investigated in particular in what concerns static and dynamic characteristics\(^4\). A preliminary study on noise sensitivity to neutron and gamma radiation on commercial MESFETs\(^5\), obviously not radiation hardened, have been performed and the results show that ENC at 20 ns, with a factor of 2 after radiation test, is comparable with that of 60 Co gamma sources\(^6\). This result was recently confirmed in a study on other type of commercial devices\(^7\). Studies of noise sensitivity on gamma radiation in foundry processes are on the way.

To illustrate on the behaviour of GaAs MESFETs at cryogenic temperatures, Fig. 1 reports the static characteristic of a 30K164 at 4K. In the same figure the simulated I-V curves of the device are shown. They correspond to a UCB GaAs MESFET model whose parameters have been extracted using a computer program (ICCAP) deriving a Semiconductor Parameter Analyzer (HP 4142A).

Fig. 1: Static current characteristics of a 30K164 MESFET at 4K. Dotted lines show the simulation according to a UCB GaAs model whose parameters have been extracted from the measurement.

3. Voltage-sensitive preamplifiers for 4K operation

The need to reduce the parasitic capacitance, the pick-up of electromagnetic interference and the thermal power injection through the connecting leads in GaAs detector, led to the development of GaAs voltage-sensitive preamplifiers which operate at 4K inside a dilution refrigerator.

Fig. 2: Circuit diagram of a 4K GaAs voltage-sensitive preamplifier used in a double-beta decay experiment with tellurium detectors.
The main feature looked for was to obtain a very low series noise while keeping low the power dissipation; preamplifier's parallel noise is not a matter of concern at cryogenic temperature. Speed is also not critical for these applications. Several versions has been in the experiments with bolometric detectors performed by the group of Milano.

Fig. 2 shows schematic diagram of the circuit developed. Series input noise is drain-source voltage and low drain current (0.6 V, 0.6 nA). A double cascaded Q2, Q3 constant amplifying stage is developed at the dynamic load Q4, Q5. A second, inverting stage to a nominal value of 52, Transistors Q7, Q8 determine a network which provides low detailed description of this preamplifier is given in the ref. 15. The preamplifier components have been originally mounted onto a ceramic substrate which showed to be very much sensitive to thermal shocks when cooled to 4 K. Ceramic substrates at 4 K has not been excluded as possible results have been obtained with using high-quality hybrid manufacturing techniques.

Fig. 3 shows the total series noise of the voltage-sensitive preamplifier at 4 K and 77 K. A noise level of 0.5 eV Hz at 100 Hz with 5% distribution and 0.3 eV Hz at 100 voltage pulse has a rise time of 40 ns. An energy spectrum of a 2223 source obtained with a 73 g TeO2 bolometric detector read-out with GaAs preamplifiers is shown in Fig. 4.

4. Charge-sensitive preamplifiers

Charge-sensitive preamplifiers in GaAs have been originally developed for high impedance bolometric detectors and other thermal detectors. Later-on they have been proposed as front-end for cryogenic liquid calorimeters taking into account the favourable noise behaviour at short shaping times and the fast speed of response and good dynamic range with low power dissipation.

In order to make an evaluation of the relative quality of different versions of charge-sensitive preamplifiers, a factor of merit can be calculated as shown below.

4.1 A factor of merit for charge-sensitive preamplifiers

In first approximation, the rise time of the response to a 0 input current is given by the following expression, which assumes a dominant pole in the open loop gain.

\[ t_r = \frac{1}{2.2 R_i (C_f + C_3 + C_2 + C_1)} \]

where \( t_r \) is the rise time of the output pulse, \( R_i \) is the preamplifier input resistance, \( C_f, C_3, C_2 \) and \( C_1 \) are the detector, input, feedback and test capacitances respectively. Taking into account that \( R_i \) is given by
where \( g_m \) is the transconductance of the input transistor, and \( C_0 \) the capacitance determining the dominant pole, the preamplifier’s transition frequency \( f_T = g_m / 2\pi C_0 \) can be calculated from (2) and (3) by measuring the rise time for a given detector aperture.

In effect,

\[
f_T = \frac{0.35 (C_T + C_0 + C_p + C_g)}{C_0} \tag{4}
\]

now, considering that \( \frac{1}{g_m} \) expresses the speed and \( U/C_T \) the charge sensitivity of the preamplifier, and that their product increases only if the gain-bandwidth product is improved, which means increasing the power dissipation \( P_0 \). It is useful to calculate for each design the factor of merit:

\[
n = \frac{f_T}{P_0} = \frac{0.35 (C_T + C_0 + C_p + C_g)}{U/C_T P_0} \tag{5}
\]

which relates the speed-sensitivity product to the power dissipation for a given detector capacitance and dynamic range. Also, a high \( n \) means low white noise which depends on \( V/U \).

The first cryogenic charge-sensitive preamplifiers were developed using exclusively GaAs devices were reported in ref. 5. It matches detector capacitances of about 10 pF, at 4 K has a minimum ENC of 20 electrons rms at 0 pF detector capacitance, and dissipates 9 mW, the response to a sin 2 \( \omega \) current has a rise time of 20 ns with 1 pF feedback capacitance and the operating temperature extends down to 1K. Fig. 5 shows the preamplifier’s ENC as a function of the chopper time at 4K. The factor of merit of this preamplifier is \( F = 75 \) MHz/W but has a low dynamic range. Recently it was used to amplify the signal of a photodiode coupled to a 15 \( \mu \)m scintillating crystal which will be used in an experiment on double-beta decay of \(^{76} \text{Se}\).

Further versions have been developed to match detector capacitances of 80 pF\( \pm 20 \) and to reach pulse amplitudes of 1 V at the receiving end of a 50 ohm coaxial cable terminated at both ends. A slow rate of 100 V/mV has been measured. In both cases transistors in parallel at the input have been used to increase the matching detector capacitance at the expense of increasing the power dissipation. The input resistance of a version optimized for a detector capacitance of 400 pF was 22 ohm and the factor of merit was about 7 MHz/mW. The ENC at 77K was 550 electrons rms at 100 ns unipolar gaussian shaping and 100 ns peak time bipolar shaping, 64 channels of the first prototype of the LAr Accelerosim calorimeter have been equipped with this instrument. A further version, smaller in size, uses 5 transistors in parallel at the input and a single cascode stage, Fig. 6.

Fig. 5: Equilibrium Noise Charge of the first GaAs charge sensitive preamplifiers developed for operation in a large temperature range down to 2K.

Fig. 6: Circuit configuration of the GaAs preamplifiers for LAr calorimetry.
144 channels of the Accordion LAr calorimeter prototype have been equipped with these preamplifiers which have been mounted onto double-sided hybrids of 15 x 17 mm². Fast signals have been read-out using 20 ns peaking time bipolar shaping. The response to a manufactured test pulse has a rise time of 5 ns as the prototype and about 10 ns in the hybrids. The leakage capacitance is C₀=33 pF, the input resistance is higher than 100 kΩ. The power dissipation is 54 mW. The factor of merit F is 20 times that of 120 V/cm was measured. As an improved hybrid using 10 MESFETs in parallel at the input was recently developed. The ENC versus detector capacitance is given in Fig 8.

For an application requiring large charge sensitivity with a low capacitance detector a preamplifier with high open loop gain was designed. The circuit configuration is shown in Fig 8 and the ENC vs Cd in Fig 9.

Fig 8: A high sensitivity charge preamplifier with a preselector of the LAr Accordion calorimeter.

Fig 9: ENC as a function of detector capacitance for the circuit of Fig 8.

It uses a double cascade configuration, and with a feedback capacitance of 100 pF it gives an input resistance of 120 kΩ with a power dissipation of about 50 mW. The factor of merit is 21 MHzmV W. All 48 channels of the preselector for the Accordion LAr calorimeter at CERN have been equipped with this circuit. Each cell has a capacitance of 16 pF. At a bipolar shaping time of 30 ns peaking time, the ENC was 800 rms electrons. The energy resolution of the detectors can be observed in Fig 10.

Fig 10: Energy spectrum reacquired in the LAr preselector for 180 GeV muons. The dashed line is the distribution of the electronic noise.
5. Monolithic preamplifiers

The first approach of the Milano group to a monolithic GaAs preamplifier was based on a monolithic array of MESFETs produced by Gigabit Logic. The 126 x 126 MOSFET contains 11 MEMSFTs of 2 GHz transition frequency. The die is mounted in a small case (10 x 10 mm2 3D module package) which is required in every MEMSFT's electrode is connected to a pin.

A charge preamplifier for a non-polar 400 Pf detector capacitance was built on a 4-layer, 15 x 15 mm2 hybrid circuit containing the FET interconnections for the chip and the passive components. Fig. 11. Using a feedback capacitance of 33 pf, a rise time of 9 ns was obtained at 77K for a detector capacitance was 400 Pf. The input resistance is therefore 20 Ohm.

![Image](image.png)

**Fig. 11:** Some examples of cryogenic low-noise preamplifiers based on GaAs MESFETs developed by the Milano group.

The noise as a function of detector capacitance for 300K and 77K are shown in Fig. 12. In the same figure, it can be observed that the preamplifier matching capacitance is 120 pf. The noise slopes are also indicated in the figure. The noise power dissipation is not excessive, the factor of merit becomes 23 MHz/mW. A chip containing two charge preamplifiers and several MEMSFTs of gate lengths from 1 to 10 µm have been processed. The FETs will be used to study the gate length dependence of the 10 noise at cryogenic temperatures, and also the dependence of noise and dynamic parameters on neutron and gamma radiation. This data is essential in applications at future accelerators LHC/CSIC. Recent results obtained by other investigations have shown that monolithic processes give much better results regarding 10 noise at 4K than that obtained with discrete, commercial devices.

![Image](image.png)

**Fig. 12:** EMI of the charge-sensitive preamplifier based on the monolithic array of MESFETs as a function of detector capacitance.

6. Conclusions

Low-noise preamplifiers based on GaAs MESFETs have been developed and tested with success either at 4 K, with bolometric detectors and photodiodes, and at 87 K with a prototype of the LAR-Accordium calorimeter. The power dissipation can be kept low without sacrificing signal or charge sensitivity, thanks to the high electron mobility of GaAs devices. A collapse effect is manifested at cryogenic temperatures in some device types limiting the maximum operating voltage. This drawback can be overcome by proper selection of devices and by careful circuit design. A first step towards monolithic integration has been taken by developing a version based on a monolithic array of MESFETs. A chip based on a QDPA process which includes two charge preamplifiers and an array of MESFETs with different geometries was recently completed and will be tested soon.

Results obtained so far are quite satisfactory although there are still many open questions. For bolometric detectors, effort will be put in reducing the 10 noise still further as it will be of benefit for high mass, high resolution detectors. For accelerator applications, work will have to be done to test how noise is affected in particular by gamma radiation as the resistance to neutron flux has been proved.
7. References


20. see V. Barelski et al, this Conference.

DEVELOPMENT OF GaAs DETECTORS FOR X-RAY ASTRONOMY

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Abstract

New developments in the field of true imaging grazing incidence x-ray optics are likely to result in a need for position sensitive spectrometers operating up to 30 keV. GaAs semiconductor detectors would be an attractive proposition if a good spectral resolution can be obtained. A brief outline of the requirements for a competitive instrument is given, followed by preliminary results obtained from some first generation detectors.

1. X-ray imaging up to 30 keV

1.1. Telescope designs

Tree imaging at x-ray energies can only be achieved using grazing incidence optics. A typical example, shown in figure 1, of an astronomical telescope using such optics is the Wide Field Camera on the ROSAT satellite. In the configuration shown, known as Wolter-Schwarzschild Type I, rays are focussed by small angle reflections from two surfaces (one hyperboloid and one paraboloid) onto a position sensitive detector. Higher energy photons need to be scattered at increasingly small grazing angles and the technique cannot be used effectively above 10 keV. Below 10 keV Si CCDs make good spectrometers with adequate spatial resolution.

Below 1 keV normal incidence imaging can be obtained by using multi-layered mirrors. These are essentially interference filters which selectively reflect a narrow wavelength band. Recently it has been proposed that multi-layer mirrors with graded layer thicknesses could be used in a grazing incidence configuration to give tree imaging up to 25-30 keV. However a new generation of thin position sensitive spectrometer would be needed to fully exploit this new capability as conventional silicon CCDs do not have sufficient stopping power at these high energies. A thin detector is needed to avoid problems with depth of focus.

1.2. Astrophysics

As the natural end point of stellar nuclear synthesis, Fe is the heaviest nucleus of significant astrophysical interest which should be detectable in various circumstances. The most energetic line expected is at ~6.0 keV from Fe XXVI. Ionisation to this degree will occur in hot plasma environments with temperatures approaching 10^6K. Such high temperature plasma is known to exist, for example in solar flare events and as hot x-ray emitting gas associated with many clusters of galaxies. Studies of the ionisation structure would enable temperatures and densities to be determined but require reasonable spectroscopic resolution to resolve the Fe XXVI and Fe XXV lines.