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GaAs MESFETs and monolithic circuits in cryogenic environments

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Abstract: We present the latest results of a research work started in 1986 in Milano, aiming at the optimisation of GaAs MESFETs and circuits for cryogenic readout of particle detectors used in experiment of high energy physics. For bolometric detectors we have been looking for low $1/f$ noise and good dynamic performance at 4 K. We want also fast speed with low white noise and high radiation resistance for the readout of liquid Argon calorimeters. An ion-implanted MESFET process was selected for the realisation of FETs and monolithic preamplifiers for the mentioned applications. The noise and dynamic parameters of the process have been determined for the first time at 4 K and 77 K. SPICE parameters have also been extracted. As a result of this work, monolithic low noise preamplifiers were designed and fabricated. The chips have been tested with a LAr detector at CERN, confirming the expected performance. Voltage-sensitive preamplifiers for 4 K have also been fabricated and will soon be evaluated. The performance of FETs and monolithic preamplifiers at cryogenic temperatures are reported.

1. Introduction.

In experimental particle physics, a certain number of particle detectors must operate at cryogenic temperatures. Bolometric detectors, used in experiments of rare events in non-accelerator physics [1], are cooled down to less than 10 mK. Their front-end electronics are in many cases located at 4 K to reduce the noise contribution due to stray capacitances, microphonics and radio frequency interference [2]. Signals produced by the detectors have their energy concentrated in the very low frequency region, typically below 1 kHz. Cryogenic liquid calorimeters, which are being developed for the future generation of particle accelerators [3], are based on the collection of the charge created by the interaction of high energy particles in the detector. LAr is the cryogen adopted as the charge drifting medium. LKr has also been considered [4]. Signals are filtered by shaping amplifiers which have narrow bandpass centered in a frequency between 1 MHz and 10 MHz. Severe requirements regarding noise, speed, power dissipation and resistance to radiation (photons and neutrons) are demanded to the readout preamplifier. This has to be located close to each detector cell, immersed in the LAr, and therefore must operate at 87 K.

In principle, some classes of solid state devices, like SiJFETs and MOSFETs, could be used for the realization of cryogenic low-noise readouts for the mentioned applications [5]. Despite of the very different signal bandwidth and operating temperatures required for those detectors, we have found GaAs MESFET technology appropriate for the realization of both types of readout. In fact, a GaAs MESFET conducts even at the lowest temperature, due to the absence of carrier freeze-out, and its high room-temperature $1/f$ noise decreases strongly upon cooling down. In addition, the high transition frequency allows fast operation and low thermal noise in the FET channel. In this paper we will overview the characteristics of GaAs MESFETs at cryogenic temperatures pointing in particular to those aspects which affect the performance of low-noise preamplifiers for very low and medium frequency applications. We will also report on the latest results obtained in monolithic GaAs preamplifiers realized with a monolithic process.

2. GaAs MESFETs at Cryogenic Temperatures.

Nature has given GaAs fundamental physical parameters which make it an attractive option for the realization of low noise, fast, cryogenic pulse amplifiers. In fact, the high electron mobility and low electric field for carrier peak velocity make it possible to obtain high transconductance to input capacitance ratios 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 speed for a given detector capacitance. In addition, the low ionization energy of dopant impurities keeps limited the freeze-out of carries even at 4 K.

Some fundamental parameters of GaAs are indicated in Table I and, to make a comparison with the well established Si technology, the corresponding values for silicon are also given. A doping level of 10^{17} cm^{-3} have been assumed in both cases [6], [7].

TABLE I

	GaAs	Si	
electron 300K mobility 77K 4K	5000 10000 3000	800 3000 nd	$\text{cm}^2 / \text{V sec}$
Electric field at peak velocity	0.7	3	$\text{V} / \mu\text{m}$
Ionization energy of dopant impurities	6	50	meV
Energy bandgap	1.4	1.1	eV

So far, only MESFETs have been used for the realization of III-V based cryogenic low noise preamplifiers for particle detectors, although other devices like AlGaAs/GaAs High Electron Mobility Transistors (HEMTs) may be used to take advantage of their impressive electron mobilities which, from a value of $6000 \text{ cm}^2 / \text{V sec}$ at room temperature can reach $3 \times 10^5 \text{ cm}^2 / \text{V sec}$ at 77 K and $2 \times 10^6 \text{ cm}^2 / \text{V sec}$ at 4 K.

The selection of a suitable MESFET process is done looking for a low series noise at low frequencies which is normally the main limiting parameter. At room 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, each one contributing with a lorentzian term $\tau / (1 + \omega^2 \tau^2)$ where τ is the characteristic time constant of the trap. At low temperatures, this dominant $1/f$ noise decreases strongly due to the exponential dependance of τ with $1/T$. A reduction of two orders of magnitude in the spectral power density when temperature decreases from 300 K to 77 K is normally observed. An additional factor of five in noise reduction generally occurs when cooling to 4 K [8].

White noise is the limiting parameter in the signal-to-noise ratio at very high frequencies or, equivalently, for fast signal shaping. The large transconductance / input capacitance ratio (ω_T) of GaAs MESFETs make 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. Some cryogenic preamplifiers have $\omega_T/2\pi$ values in excess of 800 MHz with less than 9 mW power dissipation at 77 K [9].

One effect that may constitute a severe limitation in the operation of GaAs MESFETs in cryogenic environments is the *collapse* phenomenon [10]: some devices present a change in their static characteristics after being subject to a large drain-source voltage excursion at cryogenic temperatures. This effect is due to the trapping of hot carriers in the interface between gate and drain and sets a limit on the maximum voltage excursion that a MESFET should sustain at cryogenic temperatures.

3. Monolithic GaAs process suitable for cryogenic applications.

We have characterized two GaAs processes for possible applications in the realization of cryogenic low-noise preamplifiers. A commercial ion-implanted process was selected as it proved to have good noise and dynamic performance at 4 K and at 77 K [11]. In Fig 1 we show the transconductance characteristics for the three MESFET types available in the selected process. The shift of threshold voltage, as well as the increase in the steepness of the curves, corresponding to a higher g_m/I_d ratio, can be observed. D FETs show a g_m/I_d ratio of 76 mS/mA at 77 K.

Fig 1: Transconductance characteristics of two depletion types (M, D) and one enhancement type (E) MESFET at 300 K and at 77 K. Device width is 50 μm .

The noise performance was evaluated by measuring the $1/f$ spectral power density referred to the input, $A_f \cdot 1/f$, of test devices. The parameter A_f is inversely proportional to the input capacitance C_{iss} . A factor of merit $H_f = A_f \cdot C_{iss}$ was evaluated as a function of the gate length, to determine its optimum value. The results are shown in Fig 2, in which a minimum value at about 3 μm can be noticed. This minimum suggests two $1/f$ noise sources that are competing: one inversely proportional to $L_g^{-\alpha}$ (with $1 < \alpha < 2$), as expected [8], and other noise source that increases with L_g , whose origin must be investigated.

Fig 2: Low frequency noise parameters A_f and H_f (see text) of small test devices at 4 K.

The increase of the FET width decreases the input referred noise by $\sqrt{W}$. For detectors with a large output capacitance, the best noise performance is obtained at the matching condition, i.e. when C_{iss} equals the detector capacitance. Taking into account power dissipation it can be shown [12] that C_{iss} must be $1/3$ the detector capacitance. We have developed MESFETs with up to $24000 \mu\text{m}$ in width to match detector capacitances of 400 pF . In Fig 3 we show a microphotography of a chip containing very large gate-area MESFETs that we have manufactured to evaluate the possibility of fabricating ultra low noise GaAs MESFETs for cryogenic applications [13]. The series noise was evaluated at 4 K and at 77 K , Fig 4. Note the $1/\sqrt{f}$ dependence of the noise density. At 100 Hz , the noise density level is less than $10 \text{ nV}/\sqrt{\text{Hz}}$.

Fig 3: Microphotography of an array of MESFETs with different geometries. The largest device has a gate area of $48000 \mu\text{m}^2$.

Fig 4: Noise density level referred to the input of a $3 \times 6000 \mu\text{m}^2$ ($L_g \times W$) device immersed in LHe.

The high-frequency noise spectral density at 77 K of a $3 \times 24000 \mu\text{m}^2$ device structure can be observed in Fig 5. Note the level of white noise at $0.2 \text{ nV}/\sqrt{\text{Hz}}$, and the corner frequency below 1 MHz measured at $I_d = 16 \text{ mA}$ and $V_{ds} = 1 \text{ V}$. The total input capacitance is 120 pF .

4. Monolithic low-noise preamplifiers

Using the GaAs process just described, several monolithic preamplifiers for various applications in high energy physics experiments have been realized. The FET model parameters which are necessary for the simulation of complex structures are extracted at the actual operating temperature. In this way a very precise matching between simulated and actual performance is obtained. Still, the models developed assuming room temperature operation (i.e. Statz model) are, strictly, no longer valid at cryogenic

temperatures, in particular at 4 K. To our knowledge there is no MESFET model that takes all the low temperature effects into account.

Fig 5: Series noise of two paralleled $3 \times 12000 \mu\text{m}^2$ ($L_g \times W$) MESFETs at 77 K.

For the first time a GaAs ASIC containing a group of eight low-noise preamplifiers have been used to readout the signal of a LAr preshower detector at CERN. This chip, described in ref [9], has shown excellent performance that confirmed the benefits of our approach to the cryogenic readout.

At present, we have under fabrication a low noise current preamplifier based on the large gate area FETs described above. It will be tested this summer with a prototype of a LAr calorimeter being developed for the next generation of particle accelerators. The noise level of a prototype was less than half of the existing hybrid preamplifiers used so far with the Accordion LAr detector.

A voltage preamplifier designed for 4 K, based also on large gate area MESFETs, is also under fabrication in the same run. For reasons of space we do not enter into details but refer the reader to references [13] and [2].

5. Conclusions

The use of GaAs MESFETs in the realization of cryogenic low-noise amplifiers is now well established. Monolithic integrated circuit have been designed and operated successfully at 4 K and at 87 K. By optimizing the device geometry, low-noise and high speed have been obtained, keeping low the power dissipation. The extraction of SPICE parameters at the actual operating temperature was essential for the design of the monolithic structures. Other processes different from ion-implantation might give lower level of $1/f$ noise and should be investigated.

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