GAAS® 97 • 5th European Gallium Arsenide and related III-V compounds Applications Symposium
Bologna, Italy - September 3rd-5th, 1997

"GaAs preamplifier and LED driver for use in cryogenic and highly irradiated environments."

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Abstract

A low power dissipation, fast response and reasonable noise performance GaAs MESFETs preamplifier, able to work at low temperatures (89°K) and under high radiation dosis (>10Mrad), is presented. Attention is given to noise modeling for an application to particle detectors front-end electronics. Noise optimization can be achieved through careful layout design of the preamplifier's input transistor. This preamplifier is intended to be followed by a GaAs LED-Driver both working under the same physical conditions. A GaAs preamplifier and LED driver circuit has been designed and test results are presented and discussed in this paper.

Introduction

The European LHC (Large Hadron Collider) particle physics' program created the need for low-noise, low-power dissipation and fast response preamplifiers equiping the front-end electronics of the inner detecting calorimeters [1][2] It has been shown that CMOS circuits are able to work at low temperatures (89°K) exhibiting low noise and low power performances[3], but they are very sensitive to radiation dosis due to their gate dielectric oxyde which acts as a major radiation's particles trapping center [4], driving to unexpected V_T variations and, in general, to bad transistor's operation. So, one had to investigate GaAs technologies which are able to work under high radiation dosis due to the more resistant GaAs lattice and to the absence of any oxyde in the resultant GaAs MESFETs [4][5]. Till now, other groups have reported the realisation of preamplifiers using GaAs MESFETs [6]. Our task was to investigate the possibility of realising a low-noise, low-power preamplifier in a GaAs technology. On the other hand we have proceeded in a complete modeling of the noise which should be used for the simulation of front-end electronics for particle detectors.

Furthermore the e_n series noise parameter, characterizing the preamplifiers' noise performance has been fixed to $0.3\text{nV}/\sqrt{\text{Hz}}$ at 89°K which seems to be a technological noise limit, meaning that no better performance has ever been reported. Also, the preamplifier should exhibit a minimum of 2V output voltage dynamic range at 89°K and its power dissipation should be restrained under 50mW.

Amplifier Design

Through transistor characterisation we have verified the ability of VITESSE GaAs MESFETs to work in low temperature and high radiation dosis environments. The operation of GaAs MESFETs in cryogenic temperatures is mainly due to the GaAs lattice where electrons are lighter than in Si [7]. Basic operating parameters like the V_T or the small signal dynamic gain have been measured up to 4°K. In Fig.1 one can observe that the V_T falls with temperature whereas the gain grows, meaning that, in cryogenic temperatures, for the same V_{GS} variations as in room temperature, one gets more I_D current (Fig.2). This is due to the fact that when operating in low temperatures, the frozen GaAs lattice atoms interfere less with channel electrons (with less energy loss by collisions) leaving the latter more energetic which results in higher currents. Therefore the small signal dynamic gain grows (Fig.2).

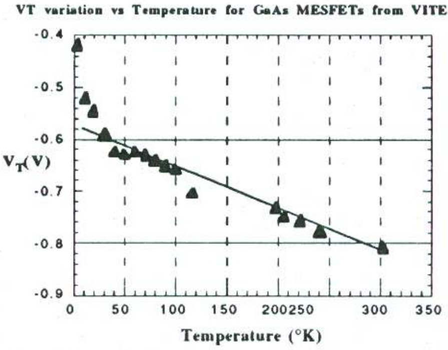

Fig.1 V_T variation at low temperatures

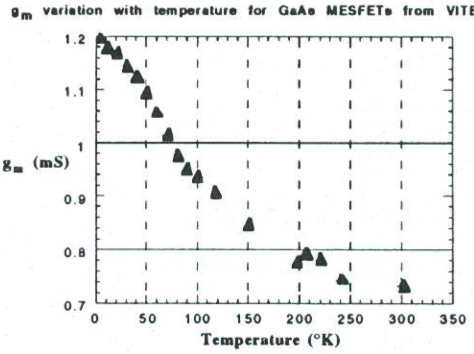

Fig.2 Small signal's dynamic gain (g_m) variation at low temperatures

Nevertheless, an analog designer should carefully consider the ±70mV ditstribution of the V_T parameter found in GaAs MESFETs due to the fact that this technology is designed for digital purposes (Fig.3).

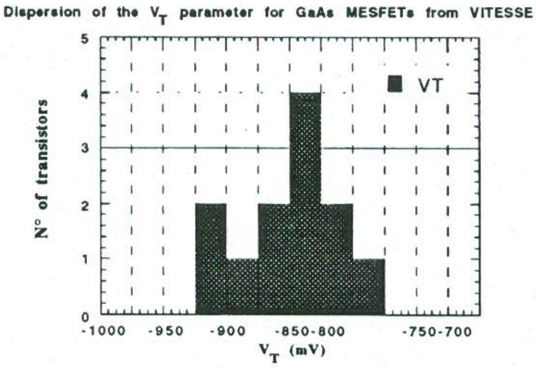

Fig.3 V_T dispersion for VITESSE GaAs technology

In our application the amplifier is used as transresistance amplifier or current to voltage converter to give a voltage proportional to the detector current [1][2] The transresistance gain is fixed by the feedback resistor Rf. At frequencies up to 1/2pRfCf the output voltage is given by Vo=I*Rf. The value of Rf is chosen taking into account the preamplifier output dynamic voltage range and the detector's current dynamic range. In order to achieve low noise, low power and high gain bandwidth operation, one stage-single input amplifiers are prefered [8][9][10]. We concluded on the design of a single input cascoded preamplifier (Fig.4).

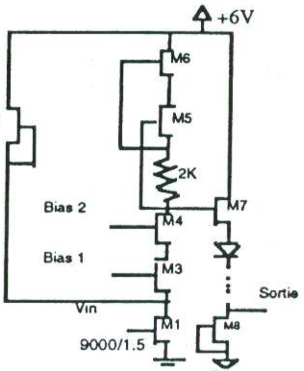

Fig.4 Preamplifier's topology

The low intrinsic gain of VITESSE GaAs MESFETs imposes the use of a double cascode to achieve an amplifier's gain higher than 500 and assure good transresistance performance [11][12][13]. Input transistor current is fixed by current source in order to optimize amplifier's power performance. Input transistor layout optimization has been achieved by designing large gate and source contact surfaces and optimized metal_2-metal_1-gate_metal contacts [14] (Fig.5).

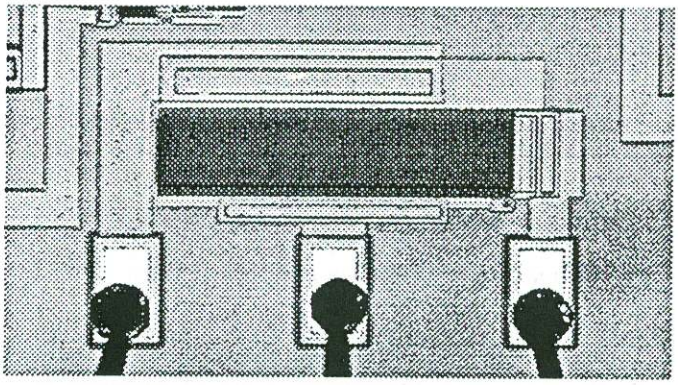

Fig.5 Optimisation of noise performance by minimizing the Rg, Rs access resistances of the input transistor.

Till today, there's no model describing MESFET's behaviour down to cryogenic temperatures. Therefore we had to extract HSPICE MESFET's parameters in liquid nitrogen temperature [19]. Diodes design requires great care in low temperature operating circuits, in particular because diode's voltage drop is found to be 800mV at 89°K instead of 600mV in room temperature. This effect is enough to cause a large reduction in the amplifier's output dynamic range. A particular diode modeling has been required to take in consideration this effect.

We've measured for the designed amplifier, a ±1% linearity (Fig.6) for 65mW of power consumption.

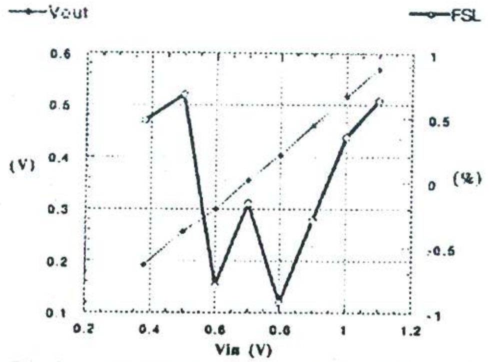

Fig.6 Preamplifier's linearity at liquid nitrogen 's temperature.

Noise considerations

Noise has been modeled by two noise sources with a parallel component (i_n) and a series component (e_n) [16]. The feedback resistance Rf is the main parallel noise source giving a current input noise of $i_{pn}(R_f)=(4kT/R_f)^{1/2}$ (1) the contribution of the MESFET gate junction's leakage current being negligeable. Another reason why shot noise may not be taken into account is that Schottky junction's leakage current decreases exponentially with temperature as has been verified by characterisation (Fig.7).

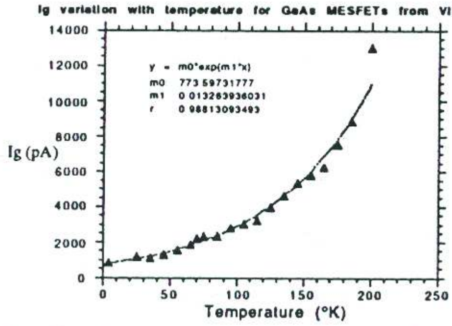

Fig.7 Gate leakage current (Ig) variation at low temperatures.

Series noise is largely dominated by the input transistor noise which encounters the transistor's equivalent noise resistance ($4kTR_{Neq}$) and the transistor's 1/f noise component ($V_{N1/f}$) [8][16]. Series noise is modeled by $e_n^2=4kTR_{Neq}+V^2_{N1/f}$ (2) corresponding to a current input noise density of $i_{sn}=e_nC_d\omega$ (3) which becomes dominant at high frequencies with respect to the detector's capacitance value Cd (Fig.8).

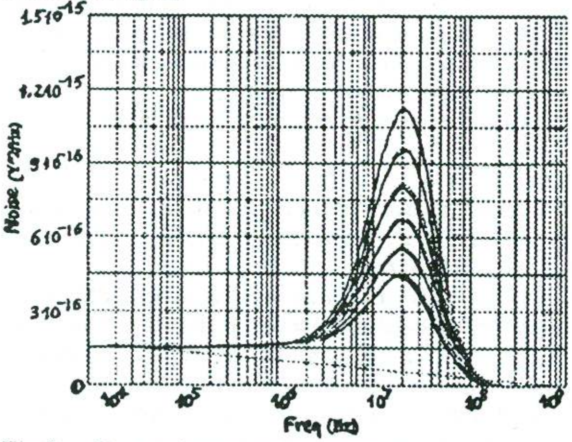

Fig.8 Transresistance noise model for increasing detector capacitances.

In the LHC case, noise optimization is achieved for 40ns signal's peaking time, which corresponds to around 40ns of shaping time (which means around 10 MHz of shaper's central frequency). In Fig.8 we observe that for these conditions, the, from the detector's capacitance induced noise, becomes the major noise source.

The transistor's equivalent noise resistance can be expressed by $R_{Neq} = R_s + R_g + R_{eqMESFET}$ where R_s, R_g stand, respectively, for the transistor's source and gate contact resistances and $R_{eqMESFET}$ stands for the equivalent thermal noise resistance which is modeled by $0.7/g_m$.. Noise sources like R_s, R_g can be minimized by a skilled layout design and a good bounding.

Series noise can be decreased with large input transistors and high bias current in order to increase g_m. Therefore noise optimization is achieved whether through increase in power consumption, whether through increase of the input transistor's width. In Fig.9 one can observe noise simulation results for two cases: In the first case, the preamplifier has a 9000/1.5 input transistor and in the second a 18000/1.5 input transistor for the same power consumption. There is a factor 2 between the e_n noise parameter of the two cases.

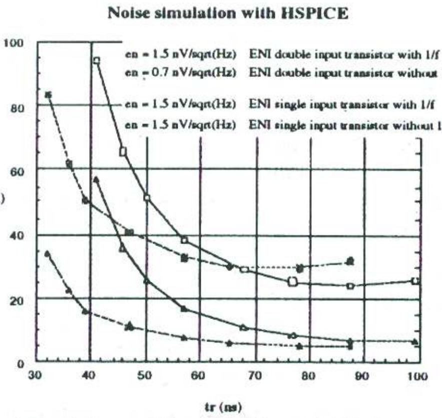

Fig.9 Simulation with and without 1/f Spice parameters.

We found VITESSE GaAs MESFET transistor's 1/f noise corner frequency to be around 200KHz. This is a good performance for a GaAs technology in comparaison to the state-of-the-art 10 years ago [17]. Nevertheless, one could pretend that an 1/f noise with 200KHz corner frequency could be neglected for applications like ours, where the shaper filters in the 1-20 MHz frequency band. But Fig.9 shows what exactly happens in reality, because 1/f noise is integrated by the detector's capacitance rising the noise level even inside the frequency band of interest. Therefore it cannot be neglected.

Otherwise a problem in the noise prediction can arise if 1/f noise is not taken in consideration during simulation. It has been found that there is a large error between e_n prediction with and without 1/f noise modeling. Fig.9 shows that e_n parameter prediction by simulation can result in a 100% error depending if one takes in consideration or not 1/f HSPICE MESFET model's parameters.

Finally, we had to test if noise simulation with HSPICE GaAs MESFET model is worth trusting: we extracted the 1/f HSPICE GaAs MESFET model's parameters by sampling the final VITESSE preamplifier noise Spectrum (Fig.10) as measured by the HP8195A Spectrum Analyzer. Then we simulated with LEVEL2 and LEVEL3 HSPICE GaAs MESFET noise models and compared the results to measurement for the same detector capacitance C_d.

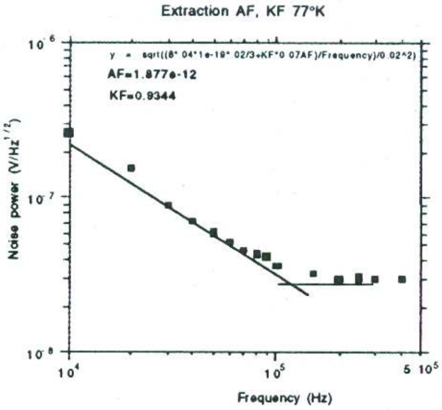

Fig.10 1/f noise parameter extraction from data taken with a HP8195A Spectrum Analyzer.

The following Fig.11 shows that simulation with 1/f HSPICE GaAs MESFET model's parameters gives a noise level very close to the measured one. Then we conclude that if 1/f noise is modeled then one could trust HSPICE simulation to give approximatively good results in noise level estimation.

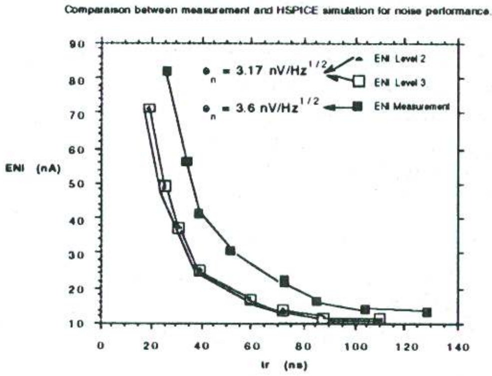

Fig.11 Comparaison between simulation and test results for noise performance.

The e_n series noise parameter, for the VITESSE amplifiers, has been found to be $1.9nV/Hz^{1/2}$ (Fig.12) in liquid nitrogen temperature.

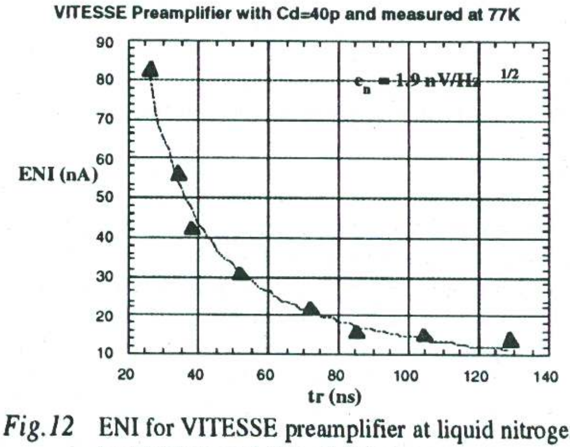

Fig.12 ENI for VITESSE preamplifier at liquid nitrogen temperature and 40p of detector capacitance.

LED-Driver Design

Few references can be found in the litterature concerning analog transmission through a fiber [18][19][20]. Most work has been done in the direction of digital optical communications [21]. A LED-Driver has been designed in the VITESSE technology to follow the preamplifier stage.

In order to improve single transistor's V-I linearity we designed a feedback enhanced V-I converter as shown in Fig.2. The feedback loop contains the AC coupled resistance R2. Then the circuit behaves as a transconductance (gm) with value gm=1/R2.

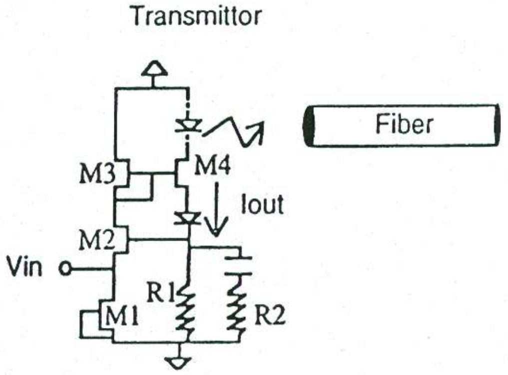

Fig 13 Optical link using GaAs LED driver

Simulation has given a driver's linearity which has been found in good agreement with test results of the designed driver. Data have been taken when the SH-LED HFE4050 photodiode was polarized with a 10mA current, where it exhibits higher linearity [19](Fig. 14).

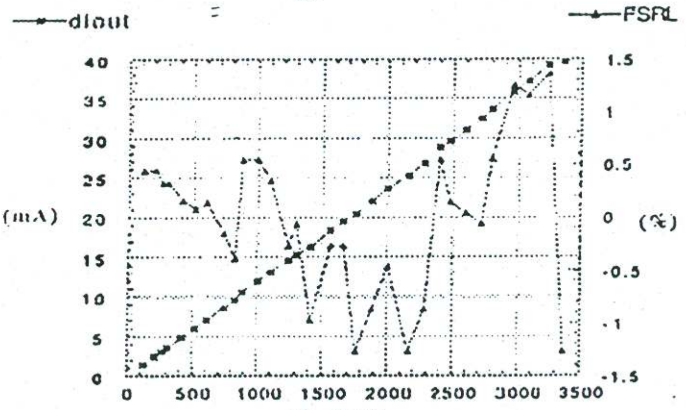

Fig. 14 Driver's linearity at liquid nitrogen's temperature

Conclusion

A GaAs, low noise, low power and high gain-bandwidth amplifier followed by a GaAs LED-Driver has been presented. Noise performance modeling is one of the key considerations that must be taken in account for such a design. Lacks in 1/f noise caracterisation may drive to wrong e_n parameter estimation. In this case where technology parameters as noise is pushed to its limits, transistor layout design should be carefully considered. We presented in this paper a method for low noise transistor design and noise prediction through simulation for front-end current sensors.

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