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SUPPLEMENTS

Monolithic GaAs current-sensitive cryogenic preamplifier for calorimetry applications.

G. Battistoni, D.V. Camin, N. Fedyakin, G. Pessina, P. Sala

INFN and Dipartimento di Fisica dell' Universitá,
via Celoria 16, 20133 Milano, Italy

We have realized low-noise monolithic GaAs preamplifiers using ion- implanted technology , to operate under low temperature and high radiation field conditions. The evaluation of noise, amplitude and timing distributions of a batch taken after first mass-production run is presented. The current-sensitive preamplifier is linear up to 8 mA of input current and able to cope a 2.2 nF detector capacitance, showing fast response (GBW product $\sim$ 1.7GHz) and very low series noise. Very good noise performance at LAr temperature is obtained by using large area MESFET ($l \cdot w = 3 \cdot 24000 \mu m^2$) as a head transistor, which exhibits at 8mA standing current and only 10mW power dissipation, intrinsic gain $\mu = g_m \cdot r_{ds} = 15$ and noise referred to the input $0.30 \div 0.35 \ \frac{nV}{\sqrt{Hz}}$. According to our estimation, second stage noise contribution is negligible. Radiation damage from neutrons and γ-irradiations as well as protection network against HV discharges are discussed.

1. Introduction

The use of current-sensitive preamplifiers (PA) for the signal readout of the Accordion LAr calorimeter has been considered as an efficient way to cope with the high rate and the large dynamic range conditions expected in ATLAS experiment at LHC [1]. The requirements for the signal readout of the LAr calorimeter (middle and back compartments of barrel) are the following

- cell capacitance C_d=1000 pF to 2500 pF;
- detector current has triangular waveform with duration ~400 ns and maximum value between 4 mA to 8 mA;
- no access for 10 years, highly reliable;
- radiation hardness (10 years): γ- 20 kRad, $5 \cdot 10^{13} \frac{n}{cm^2}$;
- high voltage (HV) discharges possible, $E_{dch} = 3$ mJ;
- fast speed; low noise; low power dissipation;
- very uniform characteristics.

In principle, the signal delivered in a calorimeter cell can be read-out by a cold monolithic circuit, put directly on the electrodes or by a warm line-receiver PA ([2],[3]), located outside the cryostat. The first solution is very attractive to reduce intrinsic and pick-up noise, charge transfer time as well as cross -talk value (due to very low input impedance), but it imposes very severe requirements on the reliability. It is worth while to stress that the "cold" solution , making amplification of the detector current right at the cell's end, potentially manifests less risk of coherent noise , which becomes very important if one makes sum of a large number of channels. The goal of the present paper is the study of uniformity and reliability of preamplifiers realized by using ion-implanted monolithic MESFET process (TriQuint's QED/A).

2. "C4"-monolithic DPA

The cold readout circuit is based on a GaAs monolithic dominant-pole amplifier (DPA) fedback as a current-to-voltage converter. The feedback network consists of a parallel combination of a resistor R_f and a capacitor C_f, both elements external to the chip, with values chosen to give the time constant $C_f \cdot R_f \sim 20$ ns and R_f dimensioned to handle the large input current as a function of calorimeter pseudorapidity η. The

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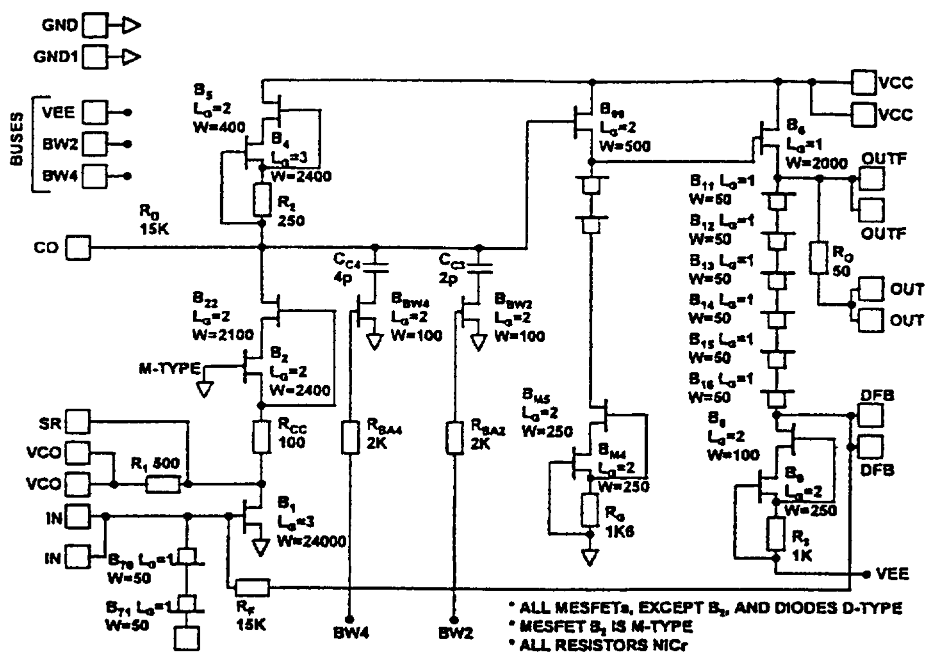

Figure 1. Circuit diagram of C4 (Nov. 1995) preamplifier.

circuit description of chip is shown on the fig.1. The input GaAs MESFET has very large gate-area ($3 \cdot 24000 \mu m^2$) and receives its bias current I_d= 8 mA from the separate power supply V_{co}. This allows us to obtain high dynamic range under low power dissipation. The gain stage consists of this large MESFET followed by a double cascode $B_2 - B_{22}$ loaded by a current source $B_4 - B_5$. It is loaded by an intermediate buffer B_{99} in turn followed by the output stage B_6. Main parameters in Liquid Argon (T=87 K) of PA can be summarized in the following way:

- GBW product (compensated): 1.7 GHz;
- series noise: 0.30~ $0.36 \frac{nV}{\sqrt{Hz}}$; f_c=0.8 MHz:
- integral nonlinearity: 0.6% at 3.2 V output signal;
- open-loop gain: ≈ 1500;
- power dissipation: 70 mW per channel;
- detector current amplification: $4 \div 10$.

Two identical preamplifiers occupy an area of 1.5·2.5 mm^2. A die, assembled into 18 pin DIL package, is shown on a microphotograph, fig.2.

3. Input transistor characterization

The noise performance of the last C4 PA version is dominated by the input transistor B_1. The contribution of second stage has been essentially reduced due to the use of $B_2 \div B_5$ transistors of larger area(dimensions are indicated in fig.1), then in previous versions([4]). To predict the noise and dynamic performance of a large number of preamplifiers, we have evaluated large area MESFET's, produced in the last three years (from 1993 to 1995) with the same monolithic TriQuint process. In Table 1 the data on MESFET's with the same current density are collected and the conclusion is that neither transconductance g_m, nor output impedance R_{ds} and as a consequence the figure of merit $\mu = g_m \cdot R_{ds}$ have

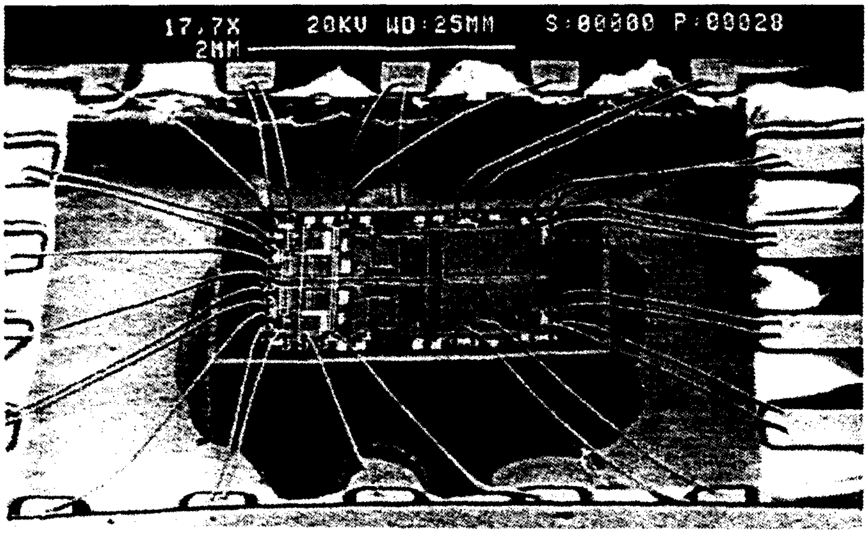

Figure 2. SEM view of the chip, which contains 2 channels and is assembled into 18 pin DIL ceramic package.

Table 2
Dependence of power dissipation (at I_d=8 mA), g_m, R_{ds}, μ and series noise e_s (at f=8 MHz) of cold GaAs MESFET's from wafer # 40 on V_{ds}.

V_{ds},V	$P = I_d \cdot V_{ds}$,mW	$g_m, \frac{mA}{V}$	R_{ds},Ohms	$\mu = R_{ds} \cdot g_m$	$e_s, \frac{nV}{\sqrt{Hz}}$
0.6	4.8	188	37	7.0	0.296
1.0	8.0	200	52	10.5	0.30
1.2	10	191	81.8	15.5	0.33
2.5	20	200	99	19.8	0.36
3.5	28	208	100	20.8	0.40

been varied over a 3 year period , which confirms good stability of the production in the foundry.

It is worth to note that transconductance of the MESFET operating in saturation region depends very little on level of doping, but this is not the case for the noise value. This is illustrated in fig.3, where the measured series noise coefficients γ ($\gamma = R_n \cdot g_m$, where R_n- is the noise resistance) of transistors produced in the different runs between 1993 and 1995 are shown as a function of the surface resistivity of the FET channel, RSD, for two different temperatures T=87 K (dark markers) and T=77 K (open markers). The window of RSD values which foundry can guarantee for mass-production is between 475 and 775 $\frac{\Omega}{sq}$, but in practice we have never seen RSD

Table 1
Input and output characteristics of MESFET's , fabricated in different runs from 1993 to 1995. T=87 K,Vds=1.2 V, Id=8 mA.

Time (length·width)	$g_m, \frac{mA}{V}$	R_{ds}, Ω	μ
Jan.93,($3 \cdot 12000 \mu m^2$)	100	158	15.8
Nov.94,($3 \cdot 24000 \mu m^2$)	181	86.5	15.6
Nov.95,($3 \cdot 24000 \mu m^2$)	191	81.8	15.5

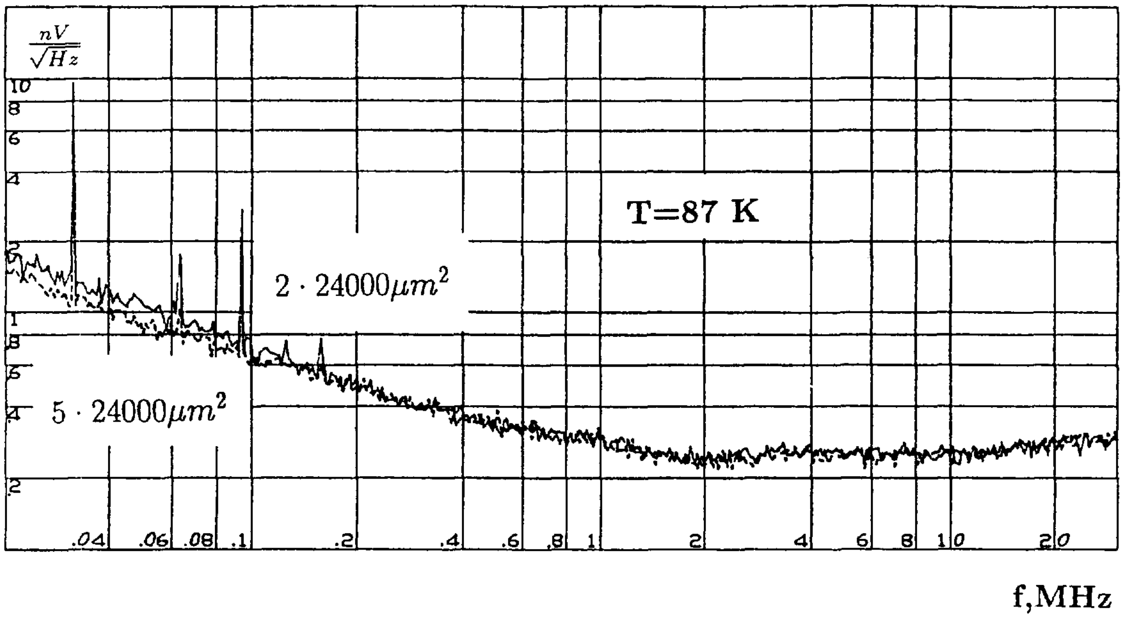

Figure 4. Noise spectra of MESFET's with area $2 \cdot 24000\ \mu m^2$ and $5 \cdot 24000\ \mu m^2$ at T=87 K.

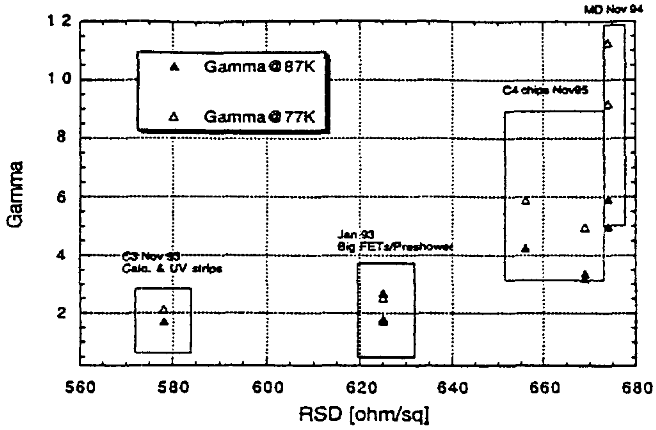

Figure 3. The dependences of series noise factor γ on surface resistance of the MESFET channel RSD for LAr and LN temperatures.

to be outside the corridor from 560 to 680 $\frac{\Omega}{sq}$. As it is seen from fig.3, the higher doping the less the noise and it's sensitivity to temperature. PAs and single MESFET's produced in November 1993 and January 1993 runs are more heavily doped and therefore have the best noise level, ever achieved with the monolithic process given.

The sensitivity of γ to 10 K temperature variation serves like a very good indicator of the doping level of transistors. The measurements performed with transistors of different area (lengths between 2 and 5 μm) produced in 1993 have also shown that the series noise e_s is not very sensitive to the value of length l in a region of white noise (see fig.4), although for low frequencies transistor with $l = 2\mu m$ exhibits a little bit higher 1/f-noise component. For that reason we have finally adopted $l = 3\mu m$ as a good compromise between transconductance , capacitance and stability of the large-area input transistor. After last foundry run (Nov.95), we have inspected how the main important parameters of large MESFET depend on a drain-source voltage V_{ds}(see Table 2).

In our last C4 PA version, V_{ds} was set to 1.2V, which is quite good compromise between μ, power dissipation P and noise referred to input e_s.

4. Evaluation of the first mass-production.

In fall 1995 we have fabricated , in a multiproject approach, four wafers (#38÷#41) of C4 DPA chips. All chips have been visually inspected, and it was verified that out of 120 chips, 105 passed

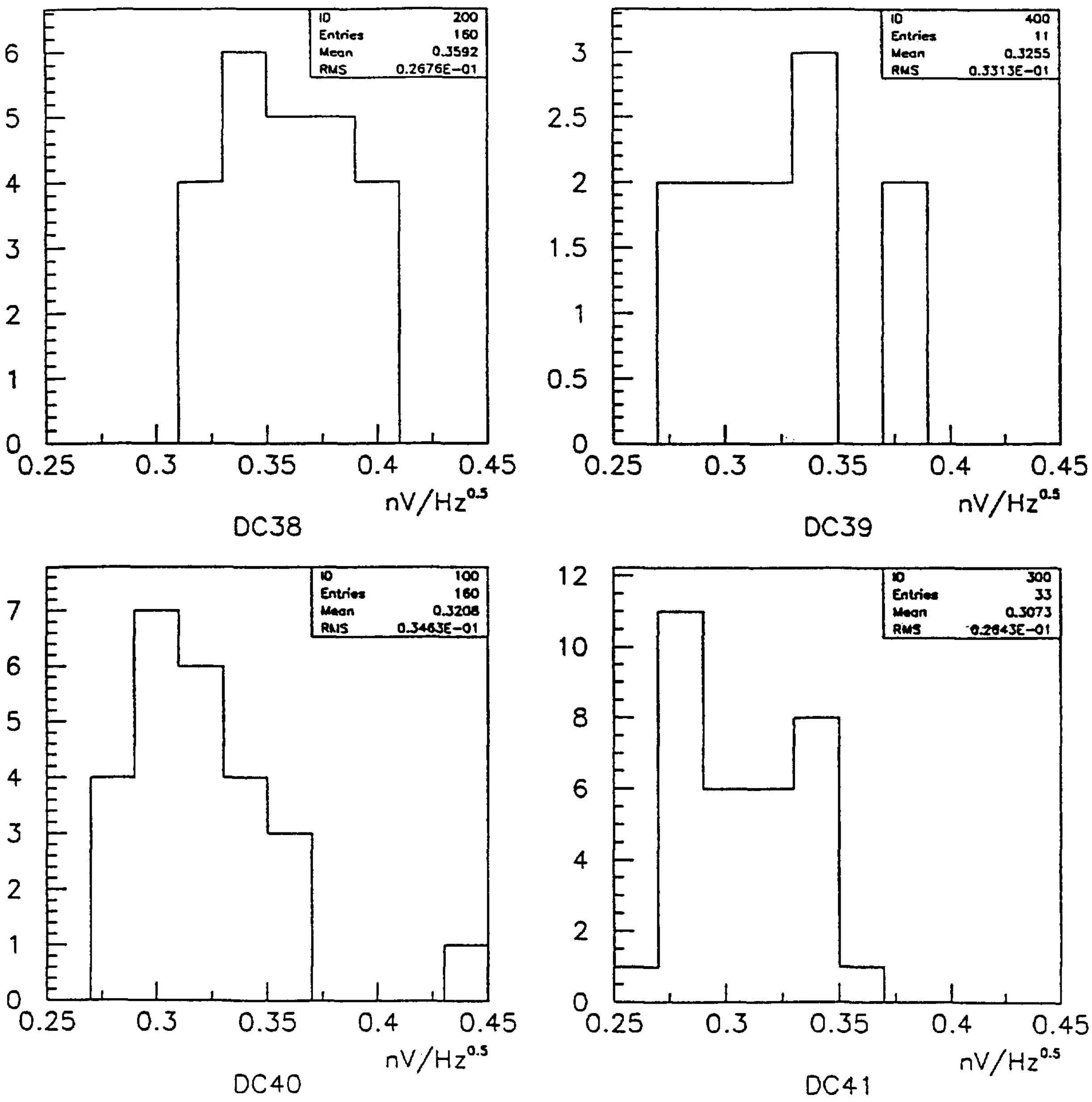

Figure 5. Series noise distributions measured in chips from W# 39÷# 41.

Table 3
Average and rms of t_p, ENI and amplitude distributions in wafers 38,39,40,41.

	t_p(5%-100%),ns		ENI at t_p, nA		Amplitude, mV	
W #	C_d=1 nF	C_d=2.2 nF	C_d=1 nF	C_d=2.2 nF	C_d=1 nF	C_d=2.2 nF
38	40.0±1.3	40.1±1.0	114±13.	222±33	287±8.9	268±13.
39	39.9±0.5	40.2±1.4	101±4.8	222±20	281±7.8	269±9.0
40	40.0±0.6	39.3±2.2	101±12.	204±19	287±9.6	267±9.4
41	40.3±1.1	39.2±1.2	100±10.	211±22	289±4.8	266±9.6

the inspection. After assembly into DIL packages, electrical income characterization was performed and only 2 chips did not work well. The resulting fabrication yield was therefore quite high,≈ 86%. The test set-up for uniformity evaluation consisted in a DPA fedback as a current-sensitive PA followed by an $RC-CR^2$ shaper with variable time constant (between 10 ns and 1μsec). An exponential current pulse (τ=400 ns, which approximately corresponds to drift time in LAr gap) was injected at the input node, which also had a capacitor C_d=1000 pF or 2000 pF simulating the detector. The peaking time t_p , pulse amplitude after the shaper and noise expressed in terms of equivalent detector current (ENI)[1] was evaluated for every unit which was identified by the wafer of origin, labelled from #38 to #41 . The results of measurements are presented in Table 3 and for details we refer to [5]. From measurements of ENI we extracted the values of series noise e_s referred to input, which are quite consistent with direct measurements of series noise spectral densities. In the fig.5 the distributions of e_s are presented for all 4 wafers.

5. Reliability of cold electronics

It is well known that operation of electronics at cold is beneficial as the matter concerns the mean time between failures, because processes like electromigration are exponentially suppressed with the temperature. But still, there are another reasons for failures, like charge-trapping and thermal stress, possible high voltage sparks in the detector and radiation damage. The first 2 items have already been discussed in detail in [5] and [6] and conclusion was drawn that charge trapping phenomena have not been observed in MESFET's produced with ion-implanted processes. Also, no reduction in C4 chip performance has been seen after collecting of 5000 chip× cycles of fast transitions between LN temperature and 320 K. Here, we briefly discuss high voltage phenomena and radiation damage.

5.1. High voltage sparks

To make the transport of free electrons in LAr media sufficiently fast and adequate to ATLAS requirements([1]), an electric field ~ 10kV/cm is applied to the gap of each cell. In case of discharge in the detector cell, the energy accumulated at the coupling capacitance connecting the electrode with PA will be delivered to the input FET. To limit the amount of energy delivered , instead of making one continuous electrode, the kapton includes a resistive coating between copper sections of smaller-area, but nevertheless the energy reaches ~3 mJ and it is sufficient to kill the readout channel. The breakdown in LAr occurs at very high electric fields, but the operating field ~10kV/cm can provoke the discharge through the surface of materials used inside the gap. That is one of the reasons why, normally, spacers are designed to have special shape, which helps to reduce gradient of field at the surface([7]). Unfortunately in Accordion the gap is very small (≈2 mm), and a mesh with short and straight walls is used to fix the gap distance. Another reason for HV discharges in the cell is boiling and bubble formation which can easily provoke partial or complete discharge of the cell.

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[1] The definition of ENI is very similar to that of ENC, with the only exception that noise at the output of shaper is referred to the amplitude of the input triangular current but not to its charge , which makes the conversion of ENI into energy resolution of electromagnetic calorimeter more straightforward compared to ENC.

In order to make the chips insensitive to HV discharges we designed a protection network (PN) , shown in fig.6, which is inserted between PA and decoupling capacitance. It consists of 2 zener diodes, a 62 nHy SMD inductor and a 1 Ω resistor. It is obvious that process of discharge of decoupling capacitance has oscillating waveform, because: a) there is always a stray inductance between cell and PA and b) after arrival of voltage overstress at the input FET , its gate-junction switches to a low-impedance state and damping condition in series LC-circuit is not fulfilled anymore. Use of zeners allows PN effectively to work for positive as well as for negative overstresses. This circuit was tested for energy of discharge up to 5.4 mJ and no degradation in performance has been seen. The results of tests are presented in Table 4. Total capacitance of zeners is ~ 100 pF, which means for C_d = 1000 pF and C_d = 2000 pF increase of noise by 10% and 5%,respectively. PN is DC coupled to preamplifier, it doesn't influence DC voltage of PA as well as signal waveform.

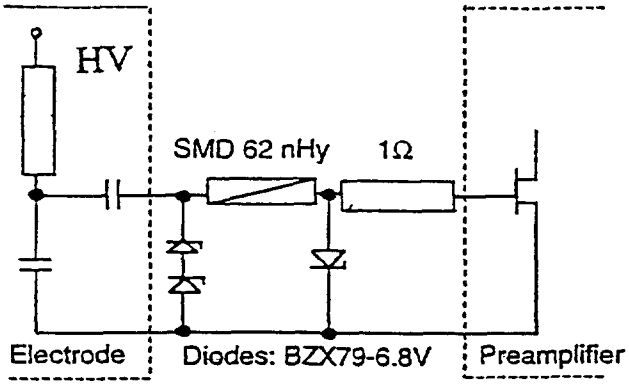

Figure 6. Schematic diagram of protection network.

Table 4
Signal, time and noise of C4 chips, measured after the shaper with variable time constant before and after HV sparks ($E_{dch} \approx 5$ mJ).

					Number of HV hits
τ_{sh},ns	15	20	30	100	
S_{max}, mV	220	254	304	304	0
τ_p, ns	35	38.5	48	98.8	
σ_n, mV	3.98	3.9	3.35	1.19	
ENI, nA	178	151	108	37	
S_{max}, mV	212	248	304	295	5500
τ_p, ns	37	42	47.8	98	
σ_n, mV	3.88	3.75	3.17	1.17	
ENI, nA	180	149	107	36.2	
S_{max}, mV	214	258	300	304	20500
τ_p, ns	34	39.4	47.6	96.8	
σ_n, mV	3.85	3.78	3.23	1.17	
ENI, nA	177	144	106	35.9	
S_{max}, mV	206	246	292	302	22500
τ_p, ns	34.5	39.4	49.3	96	
σ_n, mV	3.75	3.7	3.2	1.18	
ENI, nA	179	148	110	36.8	

5.2. Radiation resistance

We have irradiated our chips with γ (1.33,1.17 MeV) from ^{60}Co-source in BNL, with reactor neutrons ($\overline{E} = 1MeV$) in Dubna and with neutrons from stripping reaction ($^9Be(d,n)^{10}B$) (average energy $\overline{E} = 6MeV$) using SARA(Grenoble,ISN) facility. The results of measurements are presented in [8] and here we just summarize them:

- γ- irradiation increases white component of the noise with Lorentzian-like spectrum having corner frequency $f_{-3db} = 6MHz$. The spectra, before and after irradiation, are presented in fig.7a;
- n-bombardment creates defects which effectively contribute to increase of 1/f-component of noise(see fig.7b);
- pinch-off voltage of FET's is reduced with irradiation due to carrier removal effect, but drop across forward biased diode depends very weakly on irradiation;
- PA biased with a battery of diodes practically doesn't change DC output voltage.

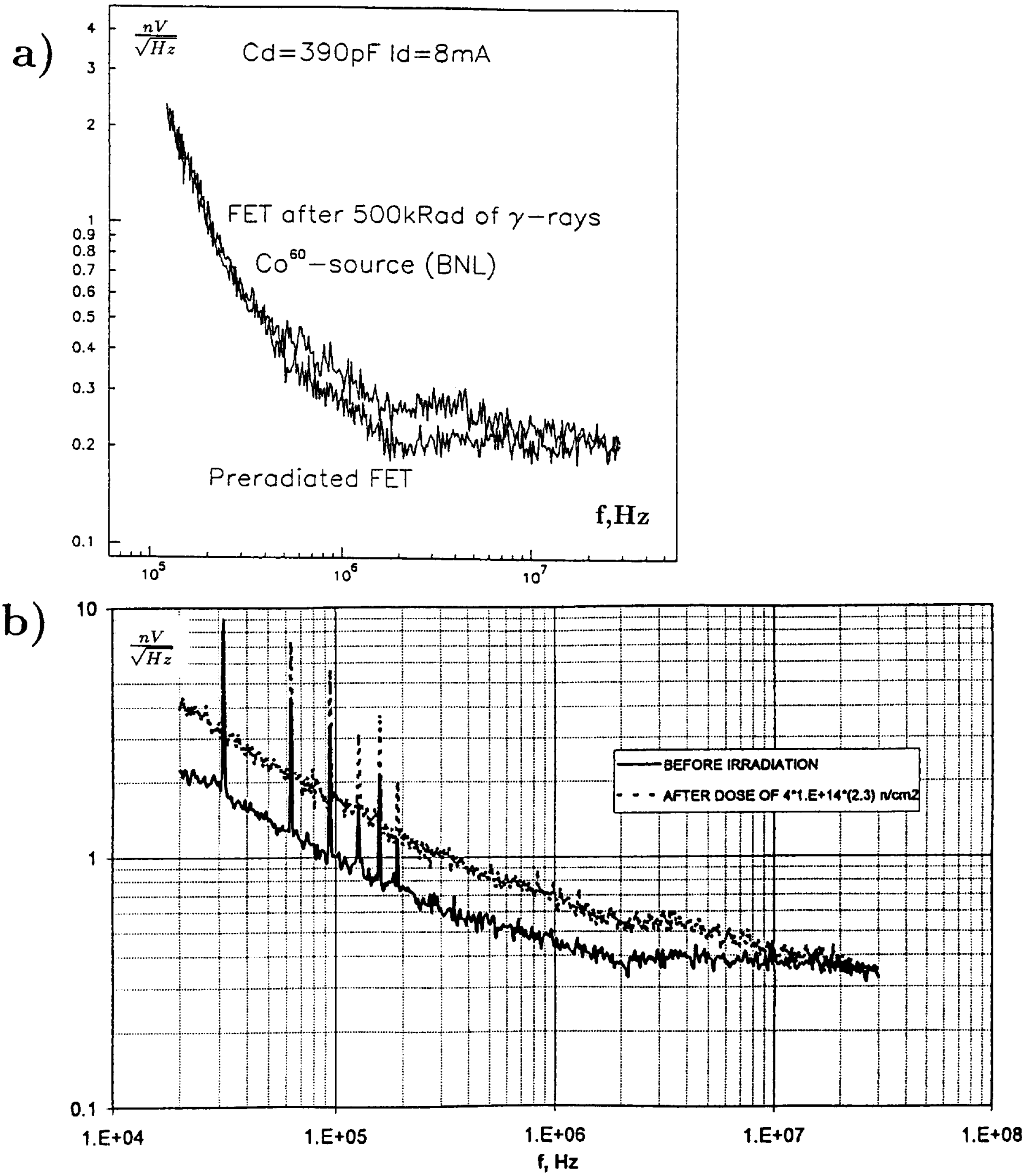

Figure 7. Spectral densities of MESFET noise referred to the input before and after γ(a)- and neutron (b) irradiations.

6. Conclusions

- a GaAs ion implanted MESFET process showed to be suitable for the fabrication of cryogenic PA for LAr calorimetry;

- the fabrication yield of cold PA's for ATLAS was larger then 85%;

- high uniformity in chip performance was verified within a wafer and between wafers, dispersion of the peaking time and gain distributions in the four wafers was below 5%, whereas the noise ranged from 5% to 15%;

- series noise referred to input is $0.30\frac{nV}{\sqrt{Hz}}$ to $0.36\frac{nV}{\sqrt{Hz}}$ at frequency f=8 MHz;

- radiation hardness is compatible with ATLAS requirements;

- efficient protection network against HV sparks is possible.

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