Effects of irradiation on the Noise and DC performance of transistors and preamplifiers based on GaAs technology¹

SU 9536

W. Karpinski, K. Lübelmeyer, D. Pandoulas, G. Pierschel, C. Rente, F. Tenbusch

I. Physikalisches Institut, RWTH Aachen, 52056 Aachen, Germany

We report measurement results with single GaAs field effect transistors and monolithic C-HFET based operational amplifiers in GaAs technology. All the devices have been exposed to neutron irradiation (1 MeV) with a total fluence of 10^{15} n/cm². The amplifiers considered here had already been irradiated either with photons from a ⁶⁰Co source for a 100 Mrad dose or with 10^{14} n/cm² neutrons. All devices remain fully functional after irradiation. We compare their amplification and noise parameters before and after the (additional) exposure of 10^{15} n/cm².

1. Introduction

The anticipated high radiation and collision rate environment at LHC places demanding requirements on the front end electronics in the central tracker and in the very forward region, with doses in excess of 100 Mrad and fluences of 10^{15} n/cm². We show in this paper that GaAs based transistors, especially metal semiconductor field effect transistors (MESFETs) and complementary high electron mobility field effect transistors (C-HFETs or C-HEMTs), show an excellent radiation hardness fully compatible with these requirements. Additional demands on these devices are low noise behaviour since it is the limiting factor for the signal to noise ratio, and low power consumption due to the high density of channels. We first compare the amplification and noise parameters for different transistor technologies. We then

examine the transistor parameters before and after an exposure to neutrons 10^{15} n/cm² peaking at 1 MeV [1] for a total fluence of 10^{15} n/cm². Finally we investigate the behaviour of operational amplifiers also exposed to 10^{15} n/cm² (part of the amplifiers had been irradiated with 10^{14} n/cm², while the rest had collected a dose of 100 Mrad photons from a ⁶⁰Co source, the results of these earlier experiments are reported in [2]). All transistors and amplifiers showed only slight changes in their parameters.

2. DC Amplification and noise parameters of different transistor technologies

In a first step we investigate the DC parameters of single transistors from different manufacturers [3,4].

manufacturer	type	size [$\mu\text{m} \times \mu\text{m}$]	I_D [mA/mm]	g_m/g_{ds}	I_g [nA/mm]
Honeywell	HFET	10 x 1	5	80	550
IAF	HFET	50 x 0.3	5	75	36
Thompson	MESFET	100 x 0.5	100	9	90

Table 2.1: Manufacturer, type, size, drain current densities I_D , voltage amplifications g_m/g_{ds} and gate leakage current densities I_g

¹supported by the German Bundesministerium für Forschung und Technologie under contract number 056AC11P

Table 2.1 lists the transistor types from the manufacturers Honeywell, Fraunhofer Institut für Angewandte Festkörperphysik Freiburg (IAF) and Thompson, as well as the type and the size (gate width x gate length) of the transistors and gives the measured values at a given drain current density I_d for the voltage amplification g_m/g_{ds} and the gate leakage current density I_g , normalized to the gate width. As seen in the table, the HFET transistors show high voltage amplification even at low drain current densities, whereas the MESFETs do not work at all at these low drain current densities. At a much higher drain current density of 100 mA/mm they show only small amplification.

Figure 2.1 shows the spectral noise densities referred to the input of the transistors and normalized to the same gate area ($100\mu\text{m}^2$). Especially in the frequency range between 10^5 and 10^7 Hz, which corresponds to readout electronics with short peaking times in the nanosecond range, no differences in the noise behaviour of the different transistor technologies is observed. However taking into account the results of table 2.1 HFETs are strongly favoured for building a low power consumption preamplifier, while maintaining high gain and high bandwidth.

Figure 2.1: Spectral noise densities for different transistor technologies normalized to the same gate area

3. Transistor parameters before and after an exposure to 10^{15} n/cm^2

We irradiated single C-HFET transistors from Honeywell technology with 10^{15} n/cm^2 (the IAF technology will be investigated in future). The irradiation was carried out at Rutherford Appleton Laboratory [1]. The energy spectrum of the neutrons peaked at 1 MeV and the transistors were biased during the irradiation ($U_{ds}=1\text{V}$, $I_d=1\text{mA/mm}$). The irradiation results due to the irradiation of 10^{15} n/cm^2 are reported in detail in [5]. All devices remained fully functional, showing only a slight change in parameters. This can be seen from figures 3.1a and b, showing the input characteristics for n-type and p-type transistors, respectively.

Figure 3.1a: Input characteristics of n-type transistors before and after 10^{15} n/cm^2

Figure 3.1b: Input characteristics of p-type transistors before and after 10^{15} n/cm^2

The arrow shows the region of very low power consumption, where we intend to operate the transistors. The characteristics show a drop of approximately 10% after irradiation with neutrons.

Figure 3.2a and b show the output characteristics of n- and p-type transistors, respectively. In both figures the lower curve corresponds to low power consumption at low drain current densities, while the upper one shows the results in the high power consumption region. For both curves a slight drop of the characteristics due to the irradiation is observed.

Figure 3.2a: Output characteristics of n-type transistors before and after 10^{15} n/cm^2

Figure 3.2b: Output characteristics of p-type transistors before and after 10^{15} n/cm^2

The transconductance g_m , the output conductance g_{ds} and the voltage amplification g_m/g_{ds} are very important

parameters in designing an amplifier. They are shown in figures 3.3a and b for n- and p-type transistors, respectively. Again the area of very low power consumption is marked by arrows. The amplification parameters show a slight shift of approximately 10% after irradiation with neutrons.

Figure 3.3a: Transconductance g_m , output conductance g_{ds} and voltage amplification g_m/g_{ds} for n-type transistors

Figure 3.3b: Transconductance g_m , output conductance g_{ds} and voltage amplification g_m/g_{ds} for p-type transistors

From these irradiation results for single transistors it can be concluded that this technology is very suitable for building an extremely radiation hard, high gain and low power consumption amplifier. The small changes of the parameters after the irradiation indicate that no special circuit design against radiation damage is required and that the devices need not to be operated in a special environment.

4. GaAs operational amplifier in C-HFET technology: Parameters before and after an exposure to 10^{15} n/cm^2

We investigated the dynamic behaviour and the noise characteristics of GaAs operational amplifiers fabricated with the same transistor technology (Honeywell) mentioned above. Figure 4.1 shows the schematic circuit diagram of the amplifier. The differential input is followed by a folded cascode and a push pull driver. The input transistors have a gate width of $330 \mu\text{m}$ and a length of $1 \mu\text{m}$.

Figure 4.1: Schematic circuit diagram of the GaAs Operational amplifier

We irradiated these amplifiers with 10^{15} n/cm^2 [5]. They had been irradiated previously with 100 Mrad of photons (^{60}Co) or with 10^{14} n/cm^2 and showed insignificant changes in the DC, AC and noise parameters due to this irradiation (reported in [2]). All amplifiers survived the additional irradiation and continued to work well afterwards (reported in [5]).

Figure 4.2 shows the dynamic behaviour of an amplifier which had been irradiated previously with 10^{14} n/cm^2 . The step answer before and after the additional neutron irradiation with 10^{15} n/cm^2 is shown. The amplifiers show only a slight drop in the rise time from 4ns to 5ns while maintaining the amplification.

Figure 4.2: Step answer of C-HFET operational amplifier before and after the additional irradiation of 10^{15} n/cm^2

Another very important parameter is the noise behaviour, since this is the limiting factor of the signal to noise ratio, especially with fast readout electronics having peaking times of the order of 40ns. We measured the equivalent noise charge (ENC) of the amplifiers with the help of a bipolar shaper. Figure 4.3 shows the ENC versus shaping time of a chip which had been irradiated previously with 100 Mrad γ 's. The ENC values before and after the additional irradiation with 10^{15} n/cm^2 are shown. The ENC measurement was performed with a stray capacitance of $C_{\text{tot}} = 11.2 \text{ pF}$ as well as with additional 10pF. The measured ENC values were fitted to obtain the individual noise contributions, i.e. the parallel noise, white serial noise and $1/f$ noise [2]. The total noise after the additional neutron irradiation increases by approximately 20%.

Figure 4.3: ENC after 100 Mrad γ 's (^{60}Co) and after an additional 10^{15}n/cm^2

The same behaviour is observed in the noise density spectra shown in figure 4.4 for the same amplifier for which the ENC values are given in figure 4.3. Here as well a parallel shift of the spectra of approximately 20% is observed, while the shape of the spectra stays the same.

Figure 4.4: Noise density spectra after 100 Mrad γ 's (^{60}Co) and after an additional 10^{15}n/cm^2

In figure 4.5 it can be seen that amplifiers which had been irradiated before with 10^{14}n/cm^2 also show only a slight increase in noise of approximately 20% after the additional 10^{15}n/cm^2 .

Figure 4.5: Noise density spectra after 10^{14}n/cm^2 and after additional 10^{15}n/cm^2

The irradiation tests indicate an excellent radiation hardness of the operational amplifiers after being exposed to the full radiation expected at LHC within 10 years of operation. The amplification and noise parameters change only slightly, and no special circuit design or environmental conditions seem to be needed to protect against radiation damage.

Conclusion:

We tested single transistors in GaAs technology from different manufacturers. Compared to MESFETs the HFETs show superior amplification at low current densities, so they are much more suitable for building a high gain and low power consumption preamplifier. We performed extensive irradiation studies with the Honeywell C-HFET technology, with single transistors as well as with operational amplifiers. The IAF technology will be investigated in the future. All the devices survived and worked well after the full radiation expected within 10 years of LHC operation. The DC parameters changed less than 10%, the AC and noise parameters by about 20%. No special care by regarding the

environment or circuit architecture was taken. So we are convinced that this technology is very well suited for front-end readout electronics at high luminosity experiments like those at LHC.

Acknowledgements:

We are indebted to Antonio Mesquida Küsters from the Institut für Halbleitertechnik I. The transistor measurements were carried out with the help of their semiconductor parameter analyser HP4145A. The C-HFET operational amplifiers were produced by Honeywell Technology Center, 10701 Lyndale Avenue South, Bloomington, Minnesota, USA. We acknowledge the efforts of Steven Baier and Bernard Grung at Honeywell. We like also to thank D. DiBitonto (University of Alabama) and K. Subhani (MIT Boston), who took part in the preamplifier development, for fruitful discussions. We wish to thank Dr. Henschel of the Fraunhofer Institut für Naturwissenschaftlich-Technische Trendanalysen for allowing us the use of their ^{60}Co -source and Dr. Michael Edwards of the Rutherford Laboratory for his excellent support in carrying out the neutron irradiation.

References:

- [1] M. Edwards et al.: The radiation hardness test facility at RAL, Proc. Large Hadron Collider Workshop, Aachen, Germany, 4.-9. Oktober 1990, CERN 90-10, Vol. III, p. 584-595
- [2] K. Lübelsmeyer et al.: Radiation and cryogenic test results with a monolithic GaAs preamplifier in C-HFET technology, NIM A 350 (1994) 530-537

[3] C. Rente et al.: Noise and DC characteristics of GaAs FETs for their use in front-end electronics at future colliders, RWTH Aachen Internal Report, PITHA 94/3

[4] F. Tenbusch et al.: Noise characteristics of radiation hard FETs for front-end electronics, RWTH Aachen Internal Report, PITHA 94/4

[5] W. Karpinski et al.: Characteristics of GaAs Complementary Heterojunction FETs (C-HFETs) and C-HFET based amplifiers exposed to high neutron fluences, RWTH Aachen Internal Report, PITHA 94/44, to be submitted to NIM