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**Characteristics of GaAs Complementary Heterojunction
FETs (C-HFETs) and C-HFET based Amplifiers
Exposed To High Neutron Fluences**

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Abstract

This paper discusses the electrical properties of complementary GaAs heterojunction FETs and of amplifiers based on these devices before and after irradiation with neutrons for a total fluence of $1.1 \cdot 10^{15} \text{ n/cm}^2$. Measurements were made on the threshold voltage, the transconductance, the saturation drain current and the gate leakage current of the discrete transistors. For the preamplifiers, DC and AC characteristics as well as their input referred noise were measured.

All devices remained fully functional after irradiation, with no anomalous behaviour. The overall change in transistor parameters after irradiation was typically 10%. The DC and AC characteristics of the amplifiers were found to remain stable after neutron irradiation. There is a slight increase in 1/f noise: For a total input capacitance of 1 pF and a shaping time of 50 ns an increase in the total ENC from 150 electrons before to 180 electrons after irradiation was measured for a preamplifier with 330 μm input FET.

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1. Introduction

C-HFET GaAs transistor technology was pioneered by Honeywell as a way of implementing CMOS-like architecture in GaAs material [1]. Ideally this would combine the advantages of CMOS circuitry (low standby power, high IC density and complexity, flexible mixed-mode functions) with the advantages of GaAs transistors (higher digital speed/power ratio and high analogue gain-bandwidth, reliability in radiation and cryogenic environments). C-HFET technology has been developed for digital circuits but its analogue aspects are not as well developed. Because of the demonstrated tolerance of this technology to very high doses of ionising radiation (>100 Mrad) and neutron fluences ($>10^{14}$ n/cm²) [2], there is considerable interest in utilising it in the LHC environment, particularly in the central trackers and in the forward region, where doses in excess of 10 Mrad/y and neutron fluences of 10^{14} n/cm²/y are expected.

This paper discusses the effects of 1MeV neutrons on the parameters of n & p channel transistors, as well as the AC, DC and noise characteristics of C-HFET based amplifiers. The effects have been studied for fluences approaching 1×10^{15} n/cm².

2. Device structure

A cross-section of the C-HFET structure is shown in Fig. 1. Starting with a 3-inch diameter semi-insulating GaAs substrate, molecular beam epitaxy (MBE) is used to grow a GaAs buffer layer, a pseudomorphic In_{0.25}Ga_{0.75}As channel, 150 Å thick, and an Al_{0.25}Ga_{0.75}As dielectric layer, 250 Å thick. As grown, all epitaxial layers are undoped except for a Silicon delta-doped layer underneath the channel which adjusts FET threshold voltages. Both n&p channel C-HFETs use WSi gates built with 1 µm gate length and Au-alloyed ohmic contacts. Insulation between devices is provided by oxygen implants. The 2-level Au-based interconnect system is insulated from the substrate by a dielectric.

The C-HFET operates in enhancement mode in a manner completely analogous to that of silicon CMOS, with the AlGaAs layer playing the role of the oxide. A gate voltage draws electrons or holes into the channel, where they are confined vertically by the AlGaAs dielectric. The carriers move laterally, and are collected by the drain. The gate voltage modulates the channel charge density above threshold, and the channel potential below threshold.[3], [4].

To evaluate the potential of this technology for analogue detector electronics a C-HFET operational amplifier was designed [5]. Fig. 2 shows the schematic diagram of the amplifier. It incorporates 25 transistors and takes advantage of the capability of the C-HFET to provide a low power consumption circuit with high gain. The basic design consists of a conventional differential input and folded cascode followed by a push-pull driver. Large input FETs are used to minimise 1/f noise. Two designs are implemented on one chip, differing only in the width of the input transistor pair. These widths were 110 µm and 330 µm. The transistors operate at low quiescent drain currents of 330 µA. The gate length of all transistors used in this circuit was 1 µm.

3. Neutron effects

The dominant effect of neutron irradiation results from elastic scattering of neutrons from semiconductor atoms producing an energetic recoil atom that loses energy by ionisation, excitation and displacement as it moves through the lattice of the semiconductor material. Two kinds of defects are created: point defects consisting of vacancy and interstitial pairs (Frenkel defects) and damage regions of various sizes consisting of spike zones of quasi metallic

behaviour [6]. These defects trap the majority carriers, thus providing recombination centres for the minority carriers and causing a reduction of their lifetime. Such a reduction is important in the operation of bipolar transistors, but is negligible for the field effect transistors considered here. However the trapping and recombination of majority carriers results also in a reduction of their density. This process of reducing the density of free carriers available for transport through the lattice is referred to as carrier removal. Hence neutron irradiation tends to make the semiconductor material more intrinsic. Moreover the majority carriers trapped at defect regions create an electric field that scatters majority or minority carriers through Coulomb scattering. Thus the third basic material effect of neutron irradiation is a decrease in carrier mobility.

The macroscopic effects of carrier removal and mobility degradation for GaAs transistors can potentially lead to: reduction in current gain, shifted I-V characteristics, increased gate leakage current, increased dynamic drain resistance, increased threshold voltage and increased $1/f$ noise.

4. Irradiation procedure

The neutron irradiation was carried out in the Rutherford Appleton Laboratory at room temperature, at a fluence rate of $7 \times 10^8 \text{ n/cm}^2/\text{s}$ leading to a total fluence of 10^{15} n/cm^2 . The neutron energy spectrum was peaking around 1 MeV [7].

We have irradiated 3 n-type transistors with the serial numbers N51, N53, N61 and 5 p-type transistors with the serial numbers P51, P53, P61, P62, P63. The gate lengths and the gate widths of the transistors were $1 \mu\text{m}$ and $10 \mu\text{m}$ respectively. All transistors were irradiated under biasing conditions with a constant drain current of $10 \mu\text{A}$ and a drain source voltage of 1V for n-type and -1V for p-type devices.

Simultaneously we have also irradiated 4 preamplifiers (1.110, 1.330, 4.110, 4.330; for purposes of identification we have labelled each amplifier by the serial number of the chip followed by the FET width) with the same total fluence and under the same conditions. During the irradiation the preamplifiers were biased to $\pm 3\text{V}$. All preamplifiers used in this study had also been irradiated in a previous experiment and the results were reported in [2]. Two of them (1.110, 1.330) had been irradiated with a ^{60}Co source for a total dose of 100 Mrad and the others (4.110, 4.330) with neutrons for a total fluence of 10^{14} n/cm^2 .

5. Measurements and Results

5.1 Transistors

The transistor parameters were measured (at room temperature) prior and after the neutron exposure using a semiconductor parameter analyser HP4145A. The following measurements were carried out:

- drain current vs drain source voltage ($I_d - V_{ds}$) curves for different gate source voltages and
- drain current vs gate source voltage ($I_d - V_{gs}$) curves for different drain source voltages.

The representative $I_d - V_{ds}$ and $I_d - V_{gs}$ curves, both before and after irradiation, are shown in Fig. 3(a, b) for n-type and in Fig. 4(a, b) for p-type transistors. The curves show that the transistors are fully functional after the irradiation with no anomalous behaviour. We notice only small changes in the drain saturation current (Fig. 3a and 4a) and a small shift of the slope of the lines in the $I_d - V_{gs}$ characteristic (Fig 3b and 4b). From the I-V measurements we have extracted the threshold voltage, the transconductance g_m , output conductance g_{ds} , and voltage amplification g_m/g_{ds} . The details are described below.

The threshold voltage (Fig. 3b, 4b; determined by linearly extrapolating the $\sqrt{I_d}$ vs V_{gs} curves to zero drain source current) is shown in Table 1. After irradiation we observe a very small increase in the threshold voltage. Its maximum shift is about 12 mV for n-type and 30 mV for the p-type transistors.

The dependence of the parameters g_m , g_{ds} , g_m/g_{ds} on the gate source voltage V_{gs} before and after irradiation is shown in Fig. 5 for n-type and in Fig. 6 for p-type C-HFETs. As seen in these Figures the amount of change due to irradiation depends on the operation region of the transistor. In a low power amplifier a part of the transistors (for example large input transistors) operate in the threshold region at low drain current densities; the other part (current sources, level shifters, etc.) are small size devices and operate in the maximum gain region. Therefore we give the irradiation results for both regions. Tables 2a, 2b and 3a, 3b summarize the extracted parameters (ΔI_d , g_m , g_{ds} , g_m/g_{ds}) before and after the neutron exposure for all investigated transistors. The data in Table 2a (2b) refer to operation of the transistors in the threshold region, at $V_{gs}=0.6V$ (-0.7V) and $V_{ds}=1V$ (-1V) for n-type (p-type) transistors respectively. Table 3a (3b) shows the same parameters near the maximum gain region, at $V_{gs}=1V$ (-1V) and $V_{gs}=1V$ (-1V) for n-type (p-type) transistors. All parameters are normalised to 1 mm gate width.

The data of Tables 2(a, b) and 3(a, b) show for the threshold region a 20% reduction in the drain saturation current for the n-type and 40% for the p-type transistors, while in the high gain region the reduction is approximately half as large.

In the threshold region the transconductance g_m decreases by about 20% for n- and 40% for p-type transistors. In the high gain region g_m is less sensitive to the neutron irradiation. Its degradation in this region is about 10% (14%) for n-type (p-type) transistors. The reason for the drop of the transconductance is the reduction of the mobility of the majority carriers in the channel caused by the trapped carriers in the transistor body and degradation of carrier concentration in the channel. In the threshold region the increase of the threshold voltage leads to an additional decrease of g_m at the given V_{gs} . The degree of decrease of transconductance and the magnitude of the threshold voltage shift is significantly smaller than observed in other heterostructure technologies [8], [9].

In spite of the degradation of g_m , the low frequency amplification factor g_m/g_{ds} for n&p-type transistors (see Tables 3a and 3b) increases generally by ~15 % after the neutron exposure (10^{15} n/cm²). This improvement results from the increase in the dynamic output resistance caused by the irradiation.

These measurements indicate that this technology is radiation hard and fully suitable for LHC environment. No special circuit architecture is needed to protect against neutron damages.

5.2 Amplifiers

5.2.1 DC and AC performance

The preamplifiers were measured before and after the additional neutron irradiation. A description of the measurement setup and the results of the previous irradiation are given in [2]. The amplifiers remain fully functional after the full exposure (10^{15} n/cm²). The results of the DC measurements before and after the irradiation are summarized in Table 4. As seen in this Table the shift of the open loop gain is of the order of 10%. The input leakage current changes slightly and remains in the nanoampere range.

Fig. 7 shows the rise time measurement data for preamplifier 1.330 before and after irradiation. No significant change in the rise time is observed.

5.2.2 Noise behaviour

The noise of the preamplifiers has been investigated using two independent methods:

- 1). The measurement of the equivalent noise charge with a variable, bipolar shaper and
 - 2). The measurement of the noise density with a spectrum analyzer.
- The two methods and the measurements setups are described elsewhere [2], [10], [11]. As

discussed there, the preamplifier noise is caused by the serial voltage source $\frac{dV_{in}^2}{df}$ and the parallel current source $\frac{dI_{in}^2}{df}$. The serial noise source is assumed to be given by:

$$\frac{dV_{in}^2}{df} = A_n + \frac{A_f}{f} + \frac{B_f}{f^2} \quad (1)$$

The parallel noise consists only of the white term and is given by:

$$\frac{dI_{in}^2}{df} = D_n \quad (2)$$

The squared equivalent noise charge referred to the input of the preamplifier can be written as:

$$ENC^2 = A_n C_{tot}^2 \frac{S_a}{\tau} + A_f (C_{tot}^2 S_c + \frac{S_e}{(R_b \parallel R_{in})^2} \tau^2) + B_f C_{tot}^2 S_d \tau + D_n S_b \tau \quad (3)$$

Here C_{tot} is the sum of the detector (C_d), stray (C_{st}), feedback (C_f) and gate-source (C_{gs}) capacitance, R_b is the biasing resistor and R_{in} is the input resistance of the amplifier, τ is the shaping time and S_a , S_b , S_c , S_d and S_e are the noise integrals, which depend mainly on the transfer function of the preamplifier-shaper system.

Fig. 8 shows the ENC data for the preamplifier 1.330 as a function of the shaping time before and after irradiation with neutrons (10^{15} n/cm^2) for two different values of the total input capacitance (11.2 pF and 21.2 pF). The measurements show the dominance of the 1/f noise. A slight shift of the ENC data to higher values demonstrates an increase of the 1/f noise as a result of the irradiation. To extract the spectral noise densities of each contribution to the total noise we performed a fit of equation (3) to the ENC data with the power densities A_n , A_f , B_f and D_n as free parameters. The results of the fit before and after irradiation (10^{15} n/cm^2) for all tested preamplifiers are summarised in Table 5(a, b). To illustrate the significance of each noise source we also converted these parameters to the equivalent numbers of electrons computed for a total input capacity of 11.2 pF and shaping time of 50 ns. The curves in Fig. 8 represent the fit results for preamplifier 1.330. The data in Table 5(a, b) show an increase of the 1/f noise contribution (parameter A_f) of the order of 40% corresponding to an increase of the ENC of about 18%. We do not see any significant change in any of the other noise contributions.

The noise densities measured with the spectrum analyzer are consistent with the ENC measurements. Fig. 9 shows the noise spectra of amplifier 1.330 before and after irradiation with 10^{15} n/cm^2 . A similar increase in the value of the 1/f noise density and no noticeable change in the form of the spectra is observed.

6. Conclusion

GaAs heterojunction C-HFET transistors and C-HFET based amplifiers have been exposed to neutrons for a total fluence of 10^{15} n/cm². The irradiation was carried out at room temperature under biasing conditions. The preamplifiers examined in this study had been irradiated in previous experiments with a ⁶⁰Co source for a total dose of 100 Mrad (1.110, 1.330) or with 10^{14} n/cm² (4.110, 4.330). After the new additional irradiation with 10^{15} n/cm² all devices remained fully functional. The overall change in the DC characteristics is of the order of 10% (14%) for n-type (p-type) transistors. There are no significant changes in the AC and DC performance of the irradiated preamplifiers. There is a slight increase in 1/f noise: for a total input capacitance of 1 pF and a shaping time of 50 ns an increase in the total ENC from 150 electrons before to 180 electrons after irradiation was measured for a preamplifier with 330 μ m input FET. These results show that C-HFET technology is fully suitable for the LHC environment. No special circuit architecture is needed to design radiation hard devices.

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Figure captions:

- Fig. 1** A cross-section of the C-HFET structure.
- Fig. 2** Schematic diagram of the C-HFET folded cascode operational amplifier.
- Fig. 3** Characteristics of the n-type C-HFET before and after neutron irradiation for a total fluence of 10^{15} n/cm².
a) I_d vs V_{ds}
b) I_d vs V_{gs} . (The insert in logarithmic scale.)
- Fig. 4** Characteristics of the p-type C-HFET before and after neutron irradiation for a total fluence of 10^{15} n/cm².
a) I_d vs V_{ds}
b) I_d vs V_{gs} . (The insert in logarithmic scale.)
- Fig. 5** Measured transconductance g_m , output conductance g_{ds} , and voltage amplification g_m/g_{ds} before and after neutron irradiation (10^{15} n/cm²) for a n-type C-HFET.
- Fig. 6** Measured transconductance g_m , output conductance g_{ds} , and voltage amplification g_m/g_{ds} before and after neutron irradiation (10^{15} n/cm²) for a p-type C-HFET.
- Fig. 7** Rise time measurement of an amplifier after irradiation with photons (100 Mrad) and after and subsequent irradiation with neutrons to a total fluence of 10^{15} n/cm².
- Fig. 8** ENC measurements for preamplifier 1.330 as a function of the shaping time after irradiation with photons (100 Mrad) and after subsequent irradiation with neutrons for a total fluence of 10^{15} n/cm². The solid line represents the results of the fit of the equation (3) to the measured data before neutron irradiation.
- Fig. 9** Input noise voltage spectra of the amplifier 1.330 after the irradiation with photons (100 Mrad) and subsequent irradiation with neutrons for a total fluence of 10^{15} n/cm².

Table captions:

- Table 1:** Measured Threshold Voltages of C-HFET Transistors at $V_{ds}= 1.0V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .
- Table 2a:** DC-Parameters of n-Type C-HFET Transistors in Threshold Region at $V_{ds}= 1.0V$ and $V_{gs}= 0.6V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .
- Table 2b:** DC-Parameters of p-Type C-HFET Transistors in Threshold Region at $V_{ds}= -1.0V$ and $V_{gs}= -0.7V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .
- Table 3a:** DC-Parameter of n-Type C-HFET Transistors in Maximum Gain Region at $V_{ds}= 1.0V$ and $V_{gs}= 1.0V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .
- Table 3b:** DC-Parameters of p-Type C-HFET Transistors in Maximum Gain Region at $V_{ds}= -1.0V$ and $V_{gs}= -1.0V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .
- Table 4** Measured DC Parameters before and after Additional Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .
- Table 5** Spectral Noise Density Parameters Obtained by the Fits to the ENC Measurements and Calculated Contributions of Each Noise Source to the Total ENC in Electrons for a Input Capacity of 11.2 pF and 50 ns Shaping Time

Transistor	V_{th} [mV] (before irr.)	V_{th} [mV] (after irr.)	$\Delta(V_{th})$ [mV]
N52	556	569	13
N53	538	550	12
N61	587	588	1
P51	-634	-648	-14
P53	-621	-632	-11
P61	-586	-622	-36
P62	-572	-608	-36
P63	-580	-612	-32

Table 1: Measured Threshold Voltages of C-HFET Transistors at $V_{ds}=1.0V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .

DC-Parameters	Transistor #		
	N52	N53	N61
I_d [mA/mm]	0.45	0.65	0.25
I_d [mA/mm](irr)	0.34	0.50	0.20
$\Delta(I_d)$ [%]	-24	-24	-19
g_m [mS/mm]	3.6	5.9	0.9
g_m [mS/mm](irr)	2.8	4.5	1.0
$\Delta(g_m)$ [%]	-23	-24	13
g_{ds} [mS/mm]	0.15	0.09	0.32
g_{ds} [mS/mm](irr)	0.10	0.06	0.23
$\Delta(g_{ds})$ [%]	-30	-36	-30
g_m/g_{ds}	24.6	66.9	2.9
g_m/g_{ds} (irr)	27.3	78.8	4.6
$\Delta(g_m/g_{ds})$ [%]	11	18	62

Table 2a: DC-Parameters of n-Type C-HFET Transistors in Threshold Region at $V_{ds}=1.0V$ and $V_{gs}=0.6V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .

DC-Parameters	Transistor #				
	P51	P53	P61	P62	P63
$-I_d$ [mA/mm]	0.11	0.15	0.34	0.38	0.39
$-I_d$ [mA/mm](irr)	0.07	0.11	0.14	0.20	0.16
$\Delta(-I_d)$ [%]	-37	-31	-57	-48	-59
g_m [mS/mm]	0.7	1.0	1.8	1.7	2.0
g_m [mS/mm](irr)	0.5	0.7	0.9	0.8	1.0
$\Delta(g_m)$ [%]	-31	-26	-49	-52	-51
g_{ds} [mS/mm]	0.09	0.14	0.23	0.39	0.25
g_{ds} [mS/mm](irr)	0.05	0.09	0.10	0.28	0.14
$\Delta(g_{ds})$ [%]	-42	-38	-56	-27	-42
g_m/g_{ds}	7.8	6.9	7.8	4.3	8.2
g_m/g_{ds} (irr)	9.3	8.2	9.0	2.9	6.9
$\Delta(g_m/g_{ds})$ [%]	19	19	15	-34	-16

Table 2b: DC-Parameters of p-Type C-HFET Transistors in Threshold Region at $V_{ds}=-1.0V$ and $V_{gs}=-0.7V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm^2 .

DC-Parameters	Transistor #		
	N52	N53	N61
I_d [mA/mm]	33.84	38.71	23.87
I_d [mA/mm](irr)	28.65	34.43	22.37
$\Delta(I_d)$ [%]	-15	-11	-6
g_m [mS/mm]	142.3	162.2	116.6
g_m [mS/mm](irr)	124.9	148.6	109.1
$\Delta(g_m)$ [%]	-12	-8	-6
g_{ds} [mS/mm]	3.55	1.86	0.98
g_{ds} [mS/mm](irr)	3.27	1.42	0.82
$\Delta(g_{ds})$ [%]	-8	-24	-16
g_m/g_{ds}	40.1	87.2	118.9
g_m/g_{ds} (irr)	38.2	104.5	133.0
$\Delta(g_m/g_{ds})$ [%]	-5	20	12

Table 3a: DC-Parameter of n-Type C-HFET Transistors in Maximum Gain Region at $V_{ds}=1.0V$ and $V_{gs}=1.0V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm².

DC-Parameters	Transistor #				
	P51	P53	P61	P62	P63
$-I_d$ [mA/mm]	3.01	3.42	4.10	3.66	4.21
$-I_d$ [mA/mm](irr)	2.58	3.00	3.22	2.80	3.33
$\Delta(-I_d)$ [%]	-15	-12	-22	-23	-21
g_m [mS/mm]	16.7	18.2	20.0	17.2	20.3
g_m [mS/mm](irr)	14.9	16.5	17.2	14.7	17.5
$\Delta(g_m)$ [%]	-11	-9	-14	-15	-14
g_{ds} [mS/mm]	0.72	0.90	1.01	1.02	1.00
g_{ds} [mS/mm](irr)	0.57	0.75	0.74	0.74	0.65
$\Delta(g_{ds})$ [%]	-21	-16	-27	-28	-35
g_m/g_{ds}	-23.1	-20.2	-19.8	-16.9	-20.3
g_m/g_{ds} (irr)	-26.1	-21.9	-23.3	-20.0	-27.1
$\Delta(g_m/g_{ds})$ [%]	13	9	17	19	33

Table 3b: DC-Parameters of p-Type C-HFET Transistors in Maximum Gain Region at $V_{ds}=-1.0V$ and $V_{gs}=-1.0V$ before and after Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm².

Preamplifier	Maximum of the open loop gain		Gate leakage current [nA]	
	before ¹	after	before ¹	after
1.110	5600	5000	1	2
1.330	5200	5000	7	5.5

Preamplifier	Maximum of the open loop gain		Gate leakage current [nA]	
	before ²	after	before ²	after
4.110	3200	3300	19	34
4.330	550	480	14.7	20

Table 4 Measured DC Parameters before and after Additional Irradiation with Neutrons for a Total Fluence of 10^{15} n/cm²

Amplifier	C _{tot} [pF]	A _n [10 ⁻¹⁸ V ² /Hz]	A _r [10 ⁻¹⁰ V ²]	B _r [10 ⁻⁶ V ² /Hz]	D _n [10 ⁻²⁶ A ² /Hz]
1.110 ¹	11.2	9.1±1.0 (905±45 el.)	3.2±0.12 (2770±50 el.)	8±1.7 (267±27 el.)	0.8±1.3 (100±100 el.)
1.330 ¹	11.2	3.9±0.45 (590±35 el.)	0.9±0.04 (1470±30 el.)	3.1±0.4 (166±10 el.)	0±0.2 (0±60 el.)
4.110 ²	11.2	4.6±0.9 (640±65 el.)	3.2±0.14 (2770±60 el.)	11±2.4 (313±34 el.)	5.5±3.1 (300±90 el.)
4.330 ²	11.2	4.0±0.43 (600±35 el.)	0.9±0.03 (1470±25 el.)	3.0±0.4 (163±10 el.)	0.0±0.2 (0±60 el.)

a) before Additional Irradiation

Amplifier	C _{tot} [pF]	A _n [10 ⁻¹⁸ V ² /Hz]	A _r [10 ⁻¹⁰ V ²]	B _r [10 ⁻⁶ V ² /Hz]	D _n [10 ⁻²⁶ A ² /Hz]
1.110 ¹	11.2	8.6±1.1 (880±55 el.)	3.7±0.13 (2980±50 el.)	7.3±1.0 (255±15 el.)	0.0±0.25 (0±70)
1.330 ¹	11.2	3.2±0.33 (520±25 el.)	1.37±0.04 (1800±30 el.)	2.8±0.3 (158±10 el.)	0.0±0.1 (0±40)
4.110 ²	11.2	4.3±0.92 (622±65 el.)	4.1±0.16 (3130±60 el.)	18±3.0 (400±30 el.)	1.9±2.3 (140±140 el.)
4.330 ²	11.2	3.5±0.4 (560±30 el.)	1.4±0.08 (1830±50 el.)	5.9±1.0 (230±20 el.)	0.0±3.0 (0±220)

b) after Additional Irradiation with Neutrons for a Total Doses of 10^{15} n/cm²

Table 5 Spectral Noise Density Parameters Obtained by the Fits to the ENC Measurements and Calculated Contributions of Each Noise Source to the Total ENC in Electrons for a Input Capacity of 11.2 pF and 50 ns Shaping Time (*in italics*).

¹ these preamplifiers had been irradiated with photons from a ⁶⁰Co source for a total dose of 100 Mrad in previous exposures.

² these preamplifiers had been irradiated with 10^{14} n/cm² in previous exposures.

Fig. 1

Fig. 2.

I_d vs. V_{ds} Characteristic before and after 10^{15} n/cm^2

Fig. 3a

I_d vs. V_{gs} Characteristic before and after 10^{15} n/cm²

Honeywell C-HFET WxL=10x1.0 μ m² n-Type Chip53

Fig. 3b

$-I_d$ vs. $-V_{ds}$ Characteristic before and after 10^{15} n/cm^2

Fig. 4a

$-I_d$ vs. $-V_{gs}$ Characteristic before and after 10^{15} n/cm²

Fig. 4b

Measurements before and after 10^{15} n/cm^2

Fig. 5

Measurements before and after 10^{15} n/cm²

Fig. 6

Rise Time Measurement

Fig.7

ENC before and after additional irradiation with 10^{15} n/cm²

Chip 1, $W_g=330\mu\text{m}$

*The amplifier was irradiated with 100 Mrad in previous experiments

Fig. 8

CHFET - CHIP 1 ($W_g=330\mu\text{m}$) before and after irradiation with neutrons

Fig. 9

The amplifier was irradiated with 100 Mrad γ (^{60}Co) previously