Noise and DC Characteristics of GaAs FET's for Use in Front-End Electronics at Future Colliders

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Abstract

Three types of GaAs transistors are compared in view of their use in preamplifiers at future collider experiments in a high radiation environment. The transistors were supplied by the three manufacturers Honeywell Inc., IAF [2] and Thomson Composants Microondes and are of the type used for production of ASIC's. The DC-characteristics and the noise of the devices in terms of the equivalent noise charge ENC are investigated. For that purpose, a charge sensitive preamplifier and a bipolar shaper with ten different shaping times ranging from 10ns up to 10μs are used in combination with an automatic measurement system.

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1 Introduction

Experiments at future colliders, like the Large Hadron Collider (LHC), require radiation hard front end electronics, which should possibly also be compatible with operation at cryogenic temperatures. Especially for detectors close to the beam-line and in the very forward region, doses of 100 Mrad and fluences of $10^{15}\frac{\text{neutrons}}{\text{cm}^2}$ are expected within the operation time. The best choice to cope with these requirements are electronics based on GaAs technology. Furthermore, GaAs transistors are able to work at liquid argon temperatures.

The signal to noise ratio and the power dissipation are important parameters of front end electronics. For example the signal expected from a MIP[3] in a GaAs detector is typically 20,000 electrons. To obtain a signal to noise ratio of 20:1, the ENC[4] of the preamplifier and the detector together has to be lower than 1000 electrons. The power dissipation is important due to the high density of channels and should be less than several mW for a single preamplifier circuit.

Due to the high density of channels, the preamplifier will be built as an integrated circuit. Therefore we have decided to examine several GaAs technologies available for ASIC's. In a first step we have concentrated on the DC-parameters[5] and the noise behaviour of the devices. In a following paper, we will investigate the radiation hardness and the performance at low temperatures.

2 DC-Measurements

The DC-measurements were performed by means of a HP4145A semiconductor parameter analyser on about ten transistors from each manufacturer. The variance of the DC-parameters concerning the gain was about 30 percent. Since the gate widths of transistors in integrated circuits can be chosen by the designer, all DC-parameters were normalized to 1mm gate width. The bias drain current of the transistor determines the power dissipation of the device and should therefore be as low as possible. With the drain source voltage being approximately 1V and the whole preamplifier consisting of about 10 transistors, the drain current should not be higher than 1mA to keep the power dissipation below 10mW, thus resulting in a maximum drain current density of 10mA/mm for a transistor of 100μm gate width.

Another important parameter is the gain of the preamplifier. The maximum gain of a single transistor is proportional to the ratio of the transconductance to the output conductance g_m/g_{ds}. In Fig. 1 typical values of these quantities are shown as a function of the drain current density for three GaAs transistors. Both HEMT's are working well down to drain current densities of 2mA/mm and have a significantly higher gain than the MESFET.

The gate leakage current density I_g should be small because of two reasons: firstly because the shot noise related to the leakage current is seen as parallel noise, and secondly because a

[3]MIP: Minimum Ionizing Particle
[4]Equivalent Noise Charge
[5]concerning gain and power dissipation

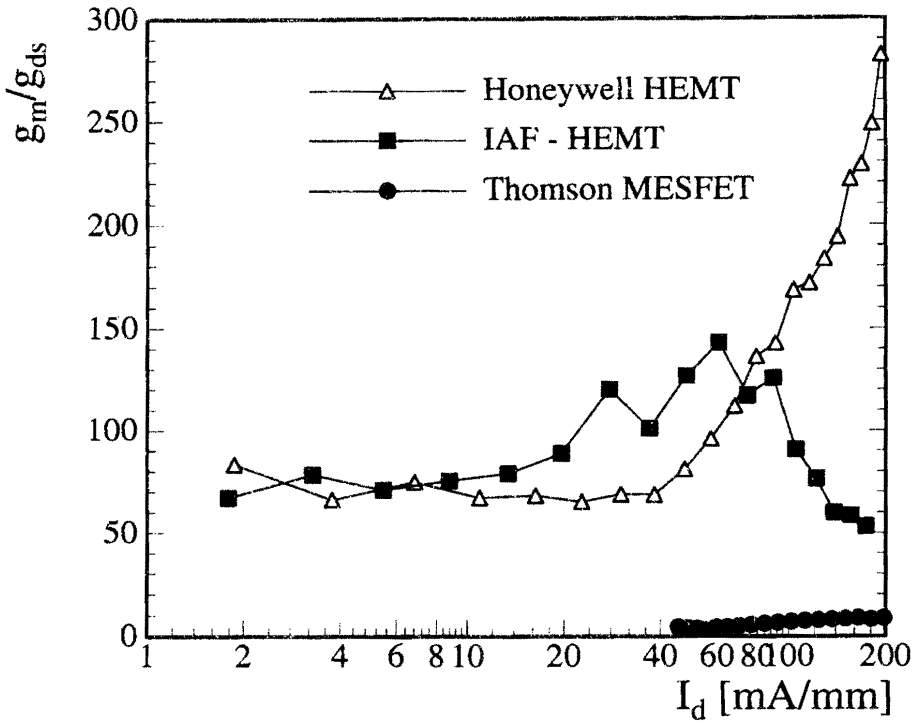

Figure 1: Gain of the three types of GaAs transistors investigated as a function of drain current

large gate current would require a small feedback resistor in a charge sensitive preamplifier, resulting in more parallel noise and in a shortening of the integration time constant of the amplifier. However, both points are not too serious in our case, since for shaping times of several tens of nanoseconds the parallel noise is not dominant and the shortening of the integration time constant is irrelevant.

In Table 1 the DC-characteristics of the three transistor types are compared for a drain current density of 5mA/mm and a drain source voltage of 3V. Since the MESFET is not working properly at these low drain current densities, its properties are given for 100mA/mm. We have chosen deliberately three different gate widths of the transistors in order to investigate their influence on the noise behaviour. The chosen values of the gate widths are all reasonably small in order to avoid oscillations of the naked transistor. Since especially the gate leakage current depends strongly on the biasing it is possible to improve these values for a single transistor by appropriate biasing. All the DC-properties given here are typical values.

It can be seen from Table 1 that the HEMTs provide a higher gain than the MESFET, whereas the gate leakage current density I_g of the Honeywell HEMT is roughly one order of magnitude higher.

manufacturer	type	size [μm]x[μm]	I_d[mA/mm]	g_m/g_{ds}	I_g[nA/mm]
Honeywell	HEMT	10 x 1	5	80	550
IAF	HEMT	50 x 0.3	5	75	36
Thompson	MESFET	100 x 0.5	100	9.0	90

Table 1: Basic properties of the investigated transistors

3 ENC-Measurements

In high energy physics experiments many detectors deliver a charge signal. It is therefore common to refer the noise to a charge at the input, known as equivalent noise charge (ENC).

For our investigations we assume that the noise is generated by the input transistor. The detector and follow-up preamplifier are taken to be noiseless. The noise is produced by three voltage and current sources which are independent from the detector capacitance and the shaper. The most important noise source $\overline{V^2}_{1/f}$ [6] is related to the 1/f-noise. The current noise source $\overline{I^2}_n$ [7] is related to the shot noise of the the gate leakage current and the thermal noise of the feedback resistor. The third noise source $\overline{V^2}_n$ [8]is caused by the thermal noise of the channel of the input transistor.

The ENC of the device is determined by the three noise sources, the detector capacitance and the transfer characteristic of the shaper and is given by [3] :

$$ENC^2 = \overline{V^2}_{1/f} C_d^2 S_c + \overline{I^2}_n S_b \tau + \overline{V^2}_n C_d^2 \frac{S_a}{\tau} \tag{1}$$

where C_d is the sum of detector, stray, feedback and gate-source capacities of the input transistor, τ is the shaping time and S_a, S_b and S_c are the noise integrals which depend mainly on the transfer function of the shaper. For the bipolar shaper we used (type CR^2RC^2), the transfer function H(s)[9] is

$$H(s) = \frac{(\tau s)^2}{(1+\tau s)^4} \tag{2}$$

and the noise integrals have the values :

$$S_a = 0.916 \qquad S_b = 0.916 \qquad S_c = 4.88\text{Hz} \tag{3}$$

Independent of the noise sources the ENC can be minimized by choosing a small input capacitance, and by optimizing the shaping time and transfer function. For example, the 1/f noise is supressed by a factor of 1.51 using a triangular shaper instead of a bipolar one. [1].

The ENC of the various transistors was measured with the experimental setup shown in Fig. 2. As a charge sensitive preamplifier, an integrated circuit (A250 from *Amptek*) is

[6]noise voltage power density at 1Hz
[7]white noise current power density
[8]white noise voltage power density
[9]H(s) is the Laplace transform of the Dirac-pulse response h(t)

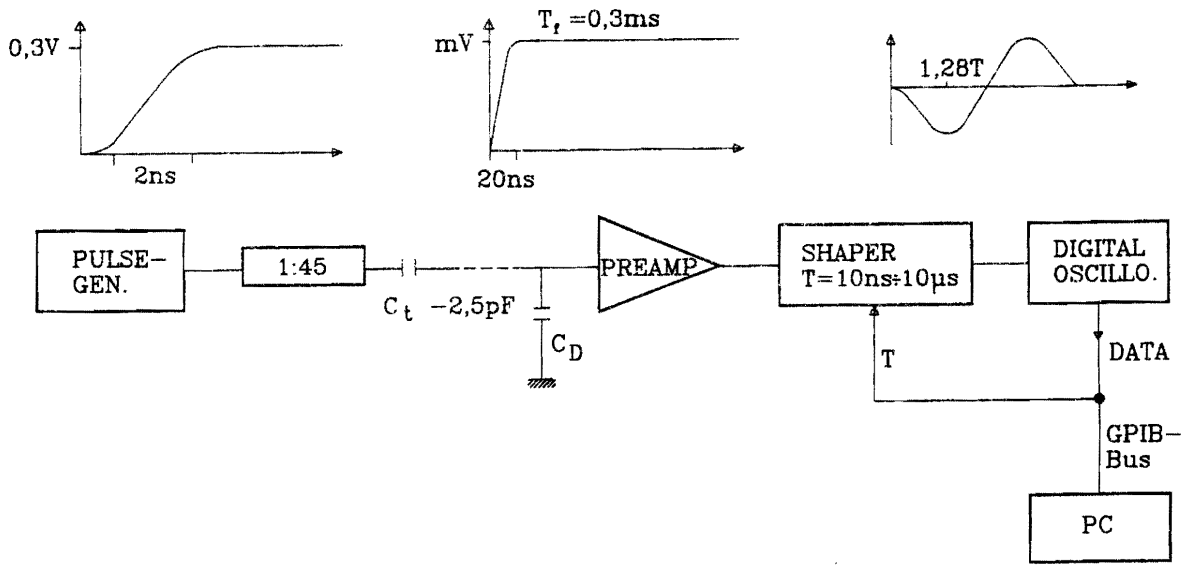

Figure 2: Experimental setup used for the measurment of the ENC

used with the transistor under investigation as discrete input transistor. The noise of the integrated circuit was found to be negligible.

The bipolar shaper is self fabricated following C. de La Taille [3], and acts also as a main amplifier with a voltage gain of approximately 250. It provides ten different shaping times : 10ns, 20ns, 50ns, 100ns, 200ns, 500ns, 1μs, 2μs, 5μs and 10μs, which can be selected by computer or from the front panel.

The computer collects the data from the HP54510 type oscilloscope via a GPIB interface and selects the shaping time of the shaper. This is done by a program which further calculates the ENC and the noise integrals.

The measurement of the ENC consists of two steps for each single shaping time: At first the transfer function of the preamplifier and the shaper is measured. For this purpose the pulse generator and the capacity C_t are connected to the input (see Fig. 2). By a voltage step with a risetime of approximately 2ns, a nearly δ-function shaped current pulse is injected into the input of the preamplifier. The voltage signal at the output of the shaper corresponds to the pulse response h(t) and is digitized and stored by the HP oscilloscope. Some hundred signals are averaged. The pulse response h(t) yields the gain β of the preamplifier and shaper and the noise integrals according to [1]. For series and parallel white noise the integrals are calculated in the time domain. For 1/f-noise the pulse response is previously transformed into the frequency domain. The noise integrals of the shaper used are found to differ only by about 10 percent from the theoretical values, except for the two shortest shaping times. For these they are about a factor of 2 higher due to the risetime of the preamplifier signal ranging from 10ns to 50ns depending on the input transistor.

In the second step the pulse generator and the capacity C_t are disconnected from the input. The noise is measured as the voltage at the output of the shaper and is digitized

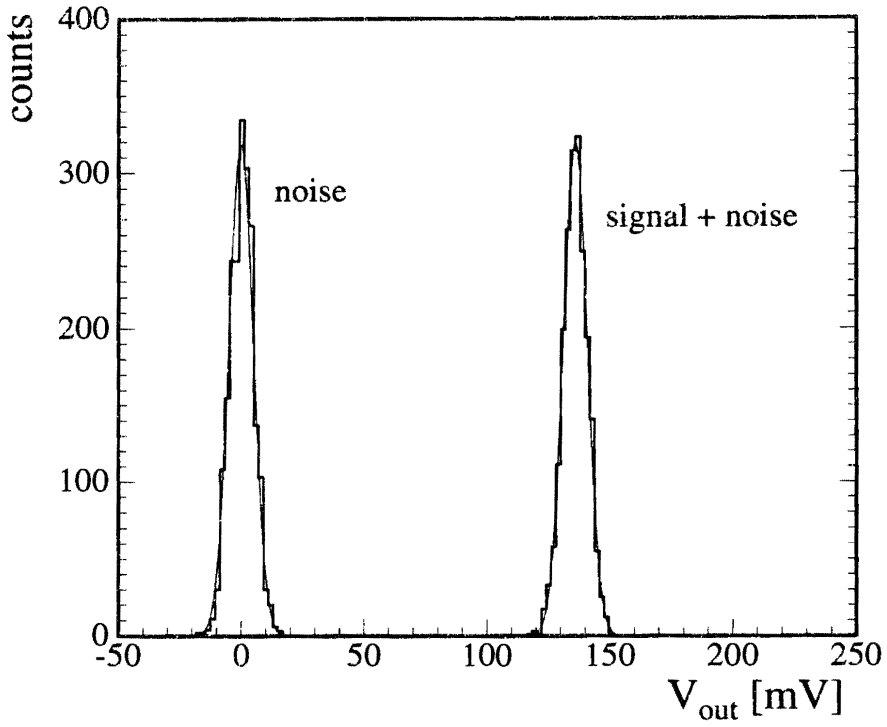

Figure 3: Output voltage with and without signal

with a sampling rate of 10,000 points/s (time interval between two sample points : 100μs) in order to avoid correlations between two sample points. About 100,000 points are taken and transmitted to the computer. Calculating the rms voltage at the output $\sqrt{\overline{v^2}_{out}}$, the ENC is then given by:

$$\mathrm{ENC} = \frac{\sqrt{\overline{v^2}_{out}}}{\beta} \tag{4}$$

This procedure is repeated for each of the ten shaping times.

To be sure that the noise without a signal is equal to the noise in the presence of one, we have measured the output voltage with and without signal. The results are shown in Fig. 3. A gaussian fit results in variances differing by only 1 percent.

4 Results

In Fig. 4 typical ENC curves are shown for the three types of GaAs transistors and a capacity C_d of approximately 14pF. The transistors were biased according to the values given in Table 1. For comparison the noise data of a silicon JFET 2SK152 are also presented. The ENC values of the three types of GaAs transistors are nearly constant with the shaping time τ, demonstrating that the 1/f-noise is the dominant noise source, in contrast to the silicon

JFET where the series white noise is most important. The difference from the ideal 1/f slope is caused by the superposition of Lorentzian spectra due to trapping centers. This can be seen more clearly in measurements of the noise power density spectrum carried out in [4]

To study the influence of fabrication tolerances on the noise behaviour, Fig. 5 shows the distribution of the ENC for a particular value of the shaping time and capacity C_d. The variance is approximately 30 percent. Similar distributions were obtained for the two other types of transistors investigated.

Since the capacity C_d is only known approximately and the gate widths of the three transistors are chosen deliberately to be different the ENC data cannot be compared directly. Because the parallel noise is negligible, it is possible to determine the series noise independently of the detector capacity by repeating the ENC measurement with an additional detector capacity of 10pF. The difference of both measurements divided by ten gives the amount of ENC for a detector capacity of 1pF. In addition the 1/f noise is inversely proportional to the square root of the gate area and accordingly the ENC values are rescaled to a gate area of $100\mu m^2$. Results for transistors of the three different manufacturers (close to the most probable ENC values of each type (see Fig.5)) are shown in Fig. 6. All three types of transistors behave similarily with the Honeywell HEMTs, having slightly more noise than the IAF HEMT and the Thomson MESFET. These two types have an ENC of about 200 electrons per picofarad detector capacity independent of the shaping time.

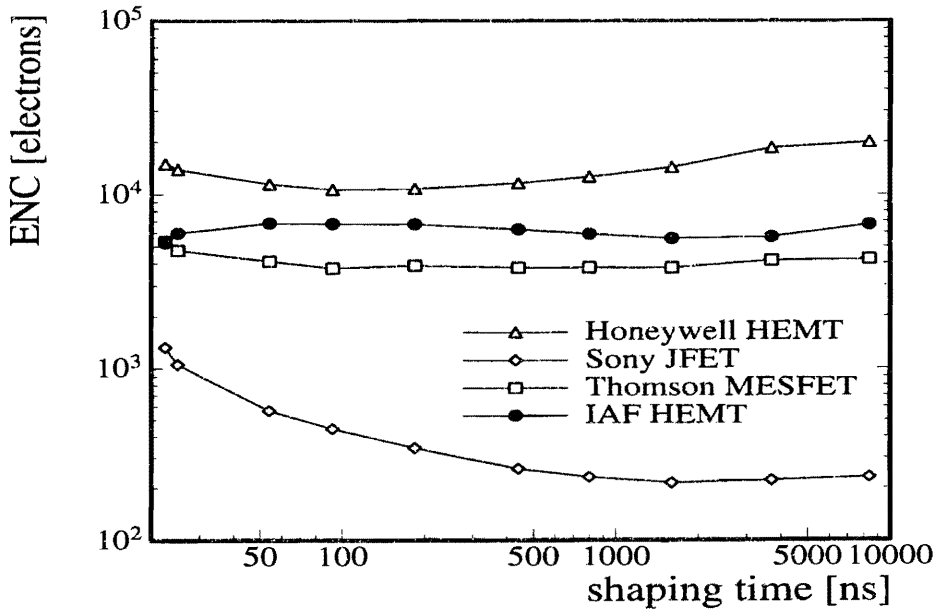

Figure 4: ENC vs shaping time for three different types of GaAs transistors and $C_d \approx 14$pF.

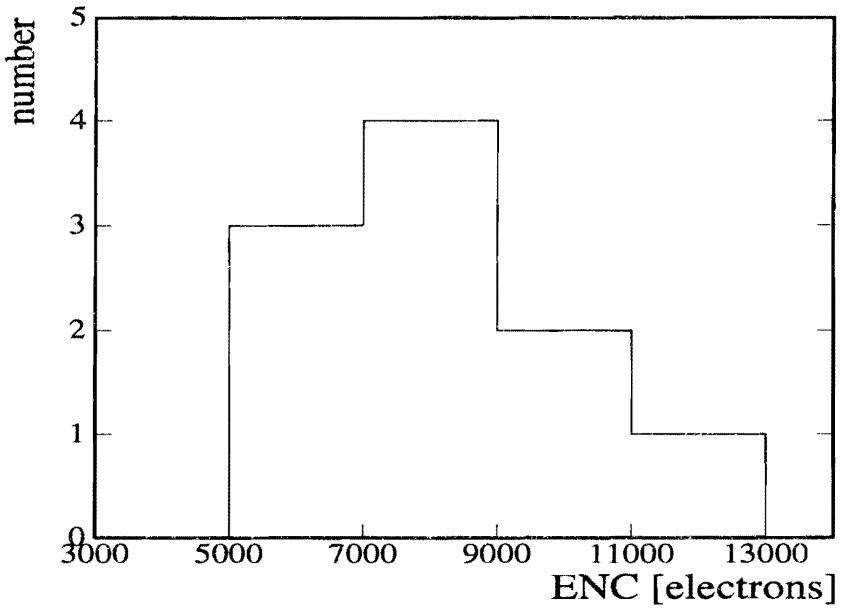

Figure 5: Distribution of the ENC of 10 HEMT's from IAF for τ=50ns and $C_d \approx$14pF

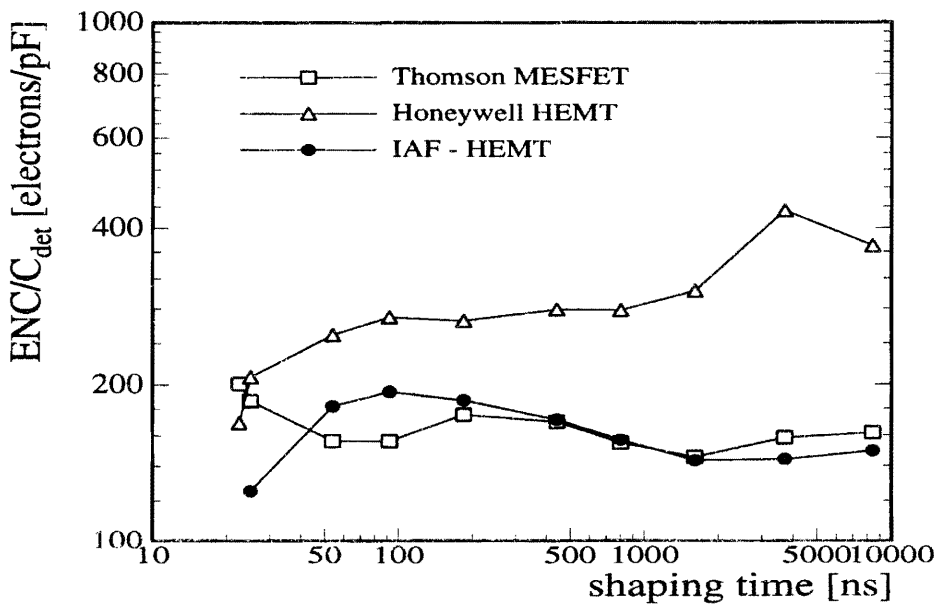

Figure 6: ENC rescaled to $100\mu m^2$ gate area and 1pF detector capacity

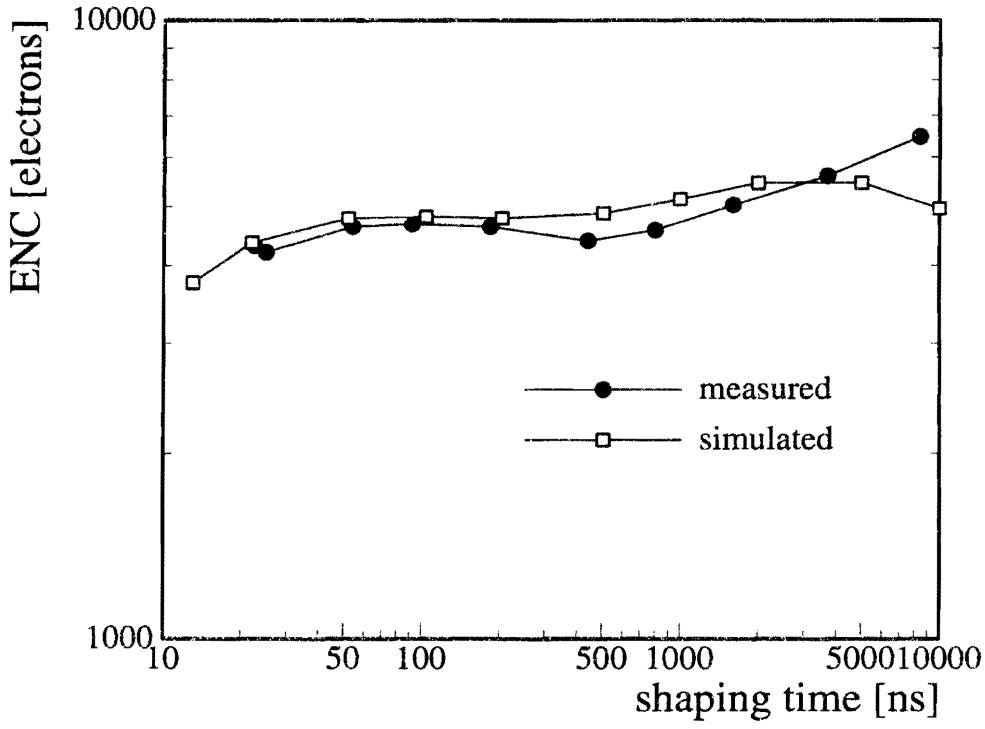

Figure 7: Comparison of simulated data from the power density spectrum with measured data. The drain current density was 30mA/mm. C_d=10pF

Fig. 7 shows simulated and measured ENC values for an IAF HEMT. The simulation was performed by means of the program *PSpice* [10] with the noise power density spectrum measured in [4].

A good agreement of the measured and simulated values of ENC is found.

Conclusion

We have investigated the noise and DC-parameters of three types of GaAs transistors and found it possible to build preamplifiers in this technology having very low power dissipation[11] and an ENC of about 200 electrons (C_{det} = 1pF, rescaled to a gate area of $100\mu m^2$). Because of their higher gain HEMTs appear to be favoured for building a low noise preamplifier with low power dissipation.

[10]PSpice circuit analysis, version 4.05, January 1991, MicroSim Corporation, California

[11]below several mW per channel

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