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Noise Spectra of SIU-GaAs Pad Detectors With Guard Rings

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On Behalf of the RD8 Collaboration

Abstract

This paper presents current noise characterization of circular pad Schottky barrier diodes with guard rings. The diodes were fabricated from undopped semi-insulating GaAs, SIU-GaAs, at the University of Glasgow. Current noise spectra were obtained for the detectors for two pad sizes, with reverse bias applied. Three measurements were also made on one of the detectors under forward bias. The noise spectra show an excess noise component, with a low frequency corner at less than 1kHz, and a flat region at higher frequencies. The magnitude of the white noise is approximately half that expected from shot noise theory for the given leakage currents. A fall in the magnitude of the noise was observed at 20kHz which is attributed to the dielectric relaxation time of the material.

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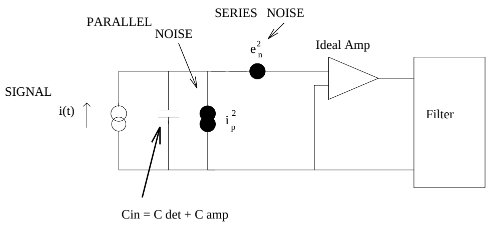


Figure 1: Equivalent circuit of the detector and amplifier for noise considerations

1 Noise theory

A detailed discussion of noise theory is given in references 1 and 2.

For any quantity *X(t)* that exhibits noise, the noise power within a unit bandwidth or power spectral density $S_X(f)$ is defined as

$$S_X(f) = \lim_{T\to\infty} \frac{\overline{2|X(f)|^2}}{T} \tag{1}$$

where *X(f)* is the Fourier transform of *X(t)*, and $\overline{|X(f)|}$ is an ensemble average. In the simplest case where the transitions that cause the noise are described by equation (2), where τ is the lifetime of the fluctuation causing interaction, the spectral density is given by equation (3).

$$\frac{-d\Delta X}{dt} = \frac{\Delta X}{\tau} \tag{2}$$

$$S_X(f) = \frac{<(\Delta X)^2> 4\tau}{(1+(2\pi f\tau)^2)} \tag{3}$$

From simple statistical considerations $<(\Delta X)^2>$ can usually be found, for example in the case of number fluctuations it is given by Poisson statistics.

This equation is very general with the condition imposed that the interactions of the electrons are independent. For small fluctuations this is indeed true and thus the Lorentzian spectrum (equation (3)) appears often. At low frequencies ($f\tau <<1$) the spectrum is white, that is independent of frequency, while at high frequencies ($f\tau >>1$) it varies as $1/f^2$, and its half power point is at $f=1/(2\pi\tau)$.

1.1 Equivalent Noise Generators

In a two terminal network, noise in a frequency interval Δf may be characterized using either an equivalent e.m.f. generator $\sqrt{S_v(f)}$ in series with the device or a current generator $\sqrt{S_i(f)}$ in parallel. An equivalent noise resistance, R_n, and an equivalent noise current, I_{eq}, may be defined

$$S_v(f) = 4kTR_n\ ,\ S_i(f) = 2eI_{eq} \tag{4}$$

where T is the room temperature and k is Boltzmann's constant.

The equivalent circuit for a detector and amplifier system is shown in figure 1 and the noise components for an FET amplifier input stage are given below.

$$S_v(f) = N_v + \frac{A_f}{f}\ ,\ N_v = \frac{3}{2}\frac{4kT}{g_m} \tag{5}$$

$$S_i(f) = N_p + \frac{B_f}{f}\ ,\ N_p = 2e(I_{det} + I_{tran}) + \frac{4kT}{R_f} \tag{6}$$

where g_m is the transistor transconductance. The equivalent noise charge of a circuit with shaping time τ, is then

$$ENC^2 = S_1 \frac{1}{\tau} {C_{in}}^2 N_v + S_2 \tau N_p + O(\frac{1}{f}) \tag{7}$$

where S_1 and S_2 depend upon the type of shaping used. Thus an an optimum shaping time exists. If S_1 and S_2 are of similar magnitude and the leakage current term dominates, a short shaping time is required. The minimum obtainable equivalent noise charge may be limited by the *1/f* noise if this term is large.

1.2 Types of noise sources

There are four noise source classifications in semiconductors: thermal, shot, generation-recombination, and modulation noise. The first three are well understood while the origin of the fourth with regard to semiconductors is less well so.

Thermal noise is a white noise source whose origin is based on fundamental thermodynamic physical laws. For a semiconductor of resistance R the spectral current and voltage noise densities are

$$S_i = \frac{4kT}{R} \quad S_v = 4kTR \tag{8}$$

Shot noise is due to the discreteness of the charge carriers and is related to the statistical nature of their injection into the semiconductor over a Schottky barrier. The origin of the spectral density may be found by considering Carson's Theorem [1]. This states that for a diode with reverse current I which equals $e < n >$, where n is the spontaneously fluctuating number of electrons that cross the barrier per second, the spectral density is given by

$$S_i(f) = 2e^2 < n >= 2eI \tag{9}$$

It can be seen that the shot noise is linearly dependent on the frequency of the electrons crossing the barrier and quadratically dependent on the charge of the pulse that the electron creates in an external circuit. The spectrum is white because of the very short transit time of the carriers across the barrier, where the barrier includes the space charge region. For the barrier to show full shot noise at all frequencies two conditions must be met. The first is that when charge carriers are injected into the material, space-charge neutrality is re-established in a very short time, given by the material dielectric relaxation time $\epsilon\rho$ [3], where ρ is the resistivity of the material. For SIU-GaAs this is of the order of 10^{-5}s. The second is that each current pulse should be able to displace a charge equivalent to that of one electron in the external circuit, that is to say a low trap density is required at the metal-semiconductor interface.

Generation-recombination noise can be understood by considering a semiconductor with a number of traps. The continuous trapping and de-trapping of the charge carriers causes a fluctuation in the number of carriers in the conduction and valence bands. The transitions are described by equation (2) and thus the noise spectral density is Lorentzian in nature, with a corner frequency given by τ_n, the lifetime of the electrons in the conduction band. The current noise density was calculated by van Vliet [4] to be

$$S_n(f) = \frac{< (\Delta n)^2 > 4\tau_n}{(1 + (2\pi f \tau_n)^2)} \tag{10}$$

where $< (\Delta n)^2 > \propto I^2$. It should be noted that in observed spectra the corner frequency of this noise is dispersed, implying a wide distribution of lifetimes. If the current that flows through a device is due to generation then the expression for the noise present will be the generation-recombination one rather than the expression for the shot noise defined in equation (9). However in most Schottky junction devices the applied voltage will increase the injection rate and the noise will show a very close resemblance to shot noise.

At low frequencies an excess noise spectral density with a *1/f* amplitude dependence is observed in semiconductors, which is known as modulation noise. As stated earlier the exact cause of this noise is still not understood.

2 The Diodes

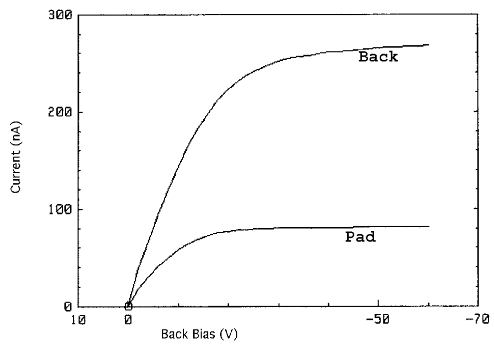
The material used for the detectors was 200μm thick semi-insulating GaAs. The detector fabrication was performed at the University of Glasgow. The detectors were designed with a circular pad contact and guard ring on top of the substrate. The bottom contact was a uniform contact that spread to the edge of the substrate. Two geometries were used, one with a pad diameter of 2mm the other of 3mm; the width of the guard was 200μm and the pad guard separation was 10μm for both diameters. The pad and guard metallization layers were identical and rectifying in nature. The reverse contact had a different recipe but was also rectifying, however its saturation current was larger than the pad's due to its larger surface area. In the following, the direction of the detector bias is quoted with respect to that of the pad. Thus reverse bias means that the pad is at a negative potential with respect to the back contact.

The *I-V* curves obtained for the diodes in reverse and forward bias are shown in figure 2. The purpose of the guard ring was to ensure that the current through the pad remained constant once in saturation. This was observed for all the samples, with the current that flowed through the pad, in the bias range 60 to 200 volts, increasing by only a few percent. For a given bias the current densities of both pads were the same and equalled 25nA/mm^2. The results showed that the saturation current density that flowed through the pad under forward bias was the same as that obtained in reverse bias.

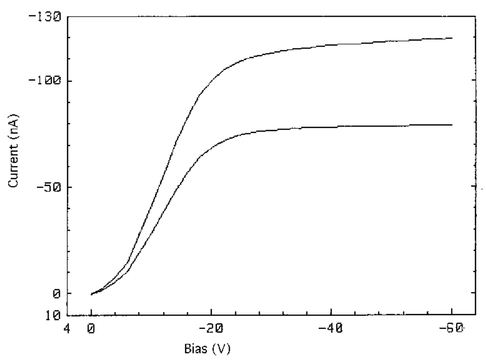
3 Measurement Procedure

To measure the current noise of the diodes under an applied bias an amplifier designed by the Politecnico di Milano was used [5]. This had a large bandwidth ($\omega_{-3dB} \simeq 20kHz$), high gain ($\simeq 86dB$), low noise ($\sqrt{v_{ni}^2} \simeq 1.8nV/\sqrt{Hz}@1kHz$) and an adjustable input bias offset. The amplifier had a large input impedance (>1GΩ) and a low output impedance (< 150Ω). This amplifier was used as an operational amplifier with a feedback resistor R_f and a feedback capacitance C_f. The output of the amplifier was passed through the high impedance input of an AC coupled oscilloscope and out through the 'scope's 50Ω output. The 'scope thus acted as a low noise voltage amplifier. The output of the 'scope was sent to a HP signal analyser with 50Ω input impedance. The feedback resistor was chosen to maximize the gain of the amplifier (large R_f), minimize the background noise due to the thermal noise of the feedback resistor (large R_f, see equation (8)) and to make sure that the amplifier did not saturate (limits R_f).

Before the current noise density spectra of the diodes were measured the transfer function and the background noise of the amplifier were determined. The transfer function was required so that the measured voltage noise could be referred back to the input as a current noise. Background noise measurements were made to show that the noise contribution from the 'scope was negligible and that the overall background noise present in normal operation was close to the thermal noise of the feedback resistor.



(a) Forward Bias



(b) Reverse Bias

Figure 2: Current-Voltage characteristics, Temp=300K

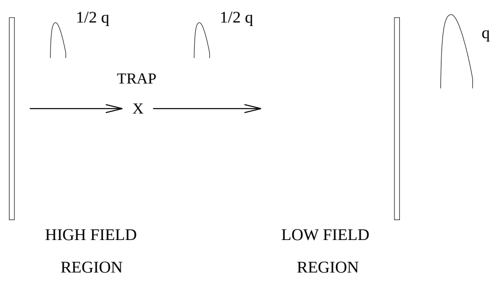


Figure 3: Simple model for shot noise.

Noise spectra were obtained for both diodes, at zero bias, under reverse bias, at the same leakage current for both diodes and under forward bias for the small diode at three leakage currents equivalent to those used for the reverse bias case.

4 Results

In this section the current noise spectral densities of the diodes are shown and some tentative interpretations of the results are proposed.

At zero bias the measured noise is the thermal noise of both the feedback resistor and the diode. From equation (4) the equivalent noise resistances of the diodes were found which with the use of the diode dimensions enabled resistivities for the material of 12.4MΩcm and 18.3MΩcm to be obtained. Both values are of the correct order of magnitude.

Figure 4 shows a typical noise spectrum. All the spectra are white at frequencies above the corner frequency of the excess noise. The value of the current noise density is less that that expected from equation (9). At a frequency of 10kHz the noise over the measured leakage current range is between 1.7 and 2.3 times less than the simple shot noise theory. At frequencies between 20kHz and 30kHz there is a corner in the white noise.

If the leakage current is due to the thermionic emission of carriers over the Schottky barrier then the noise should be shot noise. A simple model can be devised to explain the shot noise spectra obtained, with reference to equation (9) and figure 3. One can say that if an electron is trapped and at a later instant released then this electron will produce two pulses of charge whose sum is equal to e. If the electron is captured after producing a charge pulse equal to $\frac{1}{2}\,e$ in the external circuit and then released, on average the frequency of charge pulses produced by the emitted electrons is doubled while the charge is halved. The shot noise spectral density is thus reduced by a factor of two. Shot noise should be white due to the fast transit time of the electrons across the high field region behind the reversed biased Schottky junction, however, this is not observed. The corner frequency at 30kHz can be explained with reference to the condition imposed that charge neutrality is obtained in a time given by the dielectric relaxation time. Assuming that the noise source is Lorentzian, the corner frequency corresponds to the reciprocal of this time constant. Thus a lifetime of the order of 10^{-5}s is required, which is equivalent to the dielectric relaxation time in SIU-GaAs.

If the major contribution to the reverse bias leakage current is the generation current, rather than the injection of carriers over the Schottky barrier then the noise is due to generation-recombination noise from the bulk and not thermionic emission at the barrier. The noise due to generation has a characteristic time constant, the lifetime of the generated electron in the conduction band, which is inversely proportional to the corner frequency of the spectrum. If the transport mechanism is said to be by relaxation processes then the lifetime, τ_d in equation (10), is the dielectric relaxation time. Although, in principle, the dependence of the measured

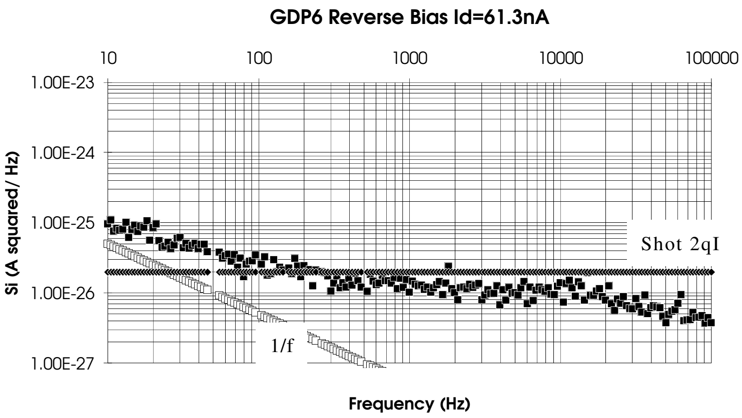


Figure 4: Typical noise spectrum of the small GaAs diode under reverse bias

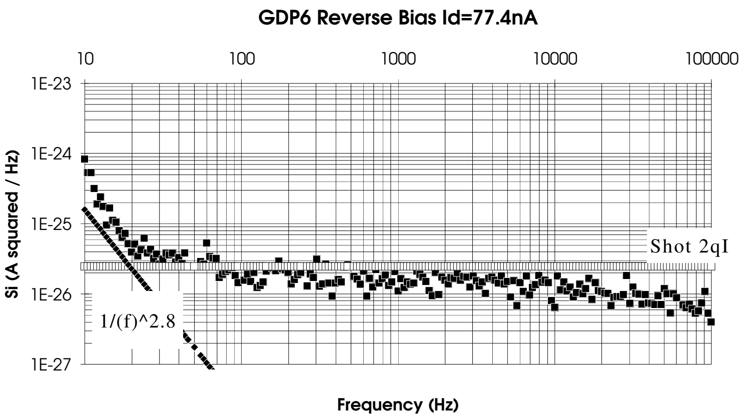


Figure 5: Spectrum showing the steep frequency dependence of the excess noise.

spectral density on the leakage current should help separate the two causes of the white noise, no clear dependence was observed.

The final part of the diode noise spectrum is the low frequency excess noise. This is seen for measurements made on the small diode for currents up to 70nA (75V bias) as approximately *1/f* noise which meets the white noise at a frequency of 500Hz. At 10Hz the excess noise is an order of magnitude greater than the white noise component of the spectrum. This is also observed in the large diode for currents up to 170nA (50V bias).

At larger currents (above 71nA for the small diode) a second low frequency noise component appears which has a much steeper frequency dependence, $1/f^\alpha$ where α is close to 3. At 10Hz the excess noise is now almost two orders of magnitude larger than the white noise. (figure 5).

The magnitude of the excess noise is seen to increase with bias towards the 'breakdown' of the diode. Here the corner frequency of the excess noise extends to much higher frequencies; 1kHz @ 230V, and >100kHz @ 240V for the small diode. The magnitude of the noise increases dramatically, to reach $3{\times}10^{-21}$ A^2/Hz at 10Hz at 230V for the small diode (see figures 6 and 7). At a bias of 200V the electric field extends across the sample to the forward biased contact which causes charge injection and thus the dramatic increase in the measured noise which occurred between 230V and 240V.

Noise spectra for the forward biased diode are similar to those obtained in reverse bias as

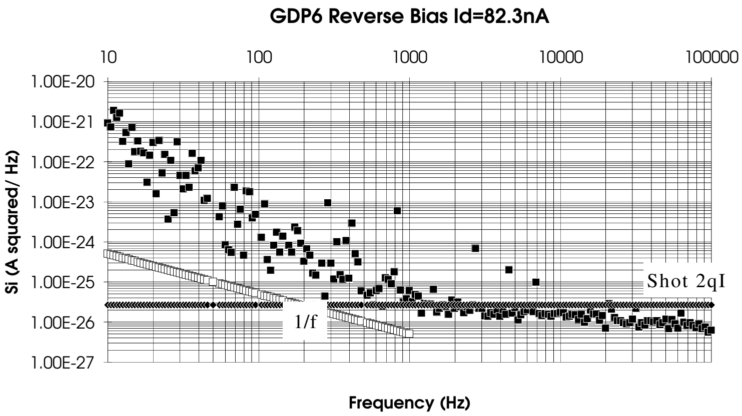


Figure 6: Noise spectrum of the small GaAs diode at a leakage current of 82nA, reverse bias of 230V.

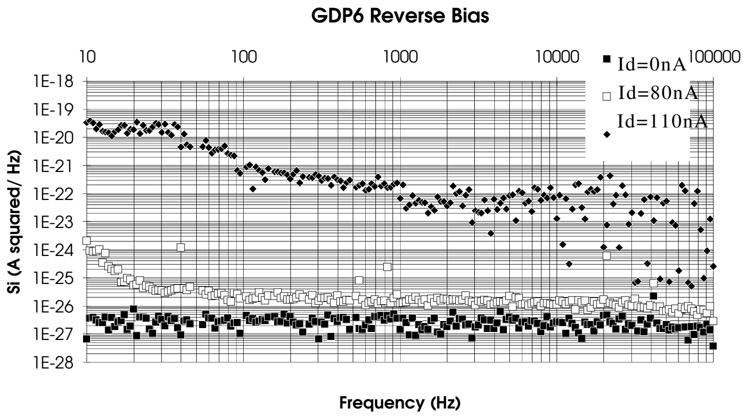


Figure 7: Noise spectra of the small GaAs diode for leakage currents of 0, 80 and 110nA.

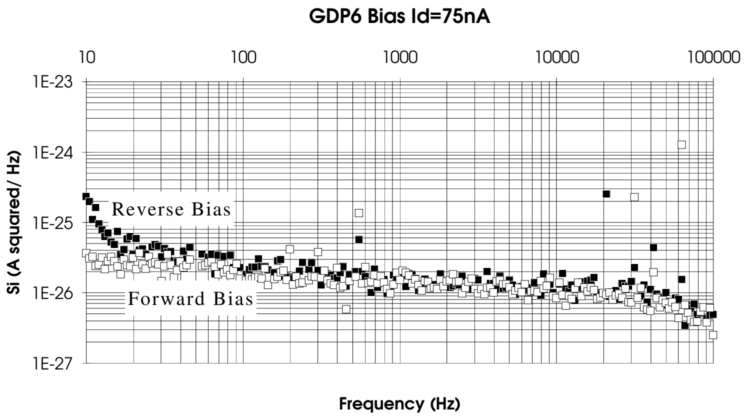


Figure 8: Noise spectra of the small GaAs diode in reverse and forward bias.

shown in figure 8. The white noise component is approximately the same, the high frequency corner is present, but no low frequency excess noise is present in the forward biased case. The reason why no excess noise is seen for the forward biased diode is not clear.

5 Conclusions and Future Work

The noise measurements show three distinct regions in the spectra, the first being the low frequency, $1/f$, excess noise which has a corner frequency of 500Hz for bias voltages below 75V. Above this the excess noise has a second component which is steeper, being almost $1/f^3$ in nature, and has a corner frequency of 50Hz which increase with bias. As the diode approaches breakdown the corner frequency and the magnitude of the excess noise increases dramatically due to injection at the forward biased contact. The second feature of the spectra is the lower than expected value of the shot noise, being about half that of simple theory. This is due to trapping of the charge carriers in the bulk which reduces the amplitude of the individual pulses that the carriers produce while increasing their frequency. The third region is the corner frequency of the white noise between 20-30kHz. This is noted to be close to the reciprocal of the dielectric relaxation time for SIU-GaAs.

Further noise measurements need to be made on more samples using different types of contacts to see if there is any correlation between the noise of the sample and the properties of the material and fabrication. Diodes that have been irradiated also need to be tested to improve the present understanding of the effects of irradiation. The technique can also be extended to examine strip detectors made from GaAs. The biasing structure used at present utilizes a punch-through mechanism via a MSM diode. There is a possibility that this may introduce more noise and it is important to understand if this is true.

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References

[1] Van der Ziel: *Fluctuation phenomena in semiconductors*
Butterworths Scientific Pub., London, (1959).

[2] M.J. Buckingham: *Noise in electronic devices and systems*
John Wiley and Sons, London, (1983)

[3] S. M. Sze: *Physics of semiconductor devices*
J. Wiley, New York, (1991).

[4] K. W. Boer: *Survey of Semiconductor Physics*
Van Nostrand Reinhold, New York, (1990).

[5] A. Longoni et al.: *To be published.*
Department of Physics, Politecnico di Milano, Milano, Italy.