

Noise as a Diagnostic Tool for Quality and Reliability of Electronic Devices

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Invited Paper

Abstract—Experimental facts about noise are presented which help us to understand the correlation between noise in a device and its reliability. The main advantages of noise measurements are that the tests are less destructive, faster and more sensitive than dc measurements after accelerated life tests. The following topics will be addressed: 1) The kind of noise spectra in view of reliability diagnostics such as thermal noise, shot noise, the typical poor-device indicators like burst noise and generation-recombination noise and the $1/f^2$ and $1/f$ noise. 2) Why conduction noise is a quality indicator, 3) the quality of electrical contacts and vias, 4) electromigration damage, 5) the reliability in diode type devices like solar cell, laser diode, and bipolar transistors, and 6) the series resistance in modern short channel MESFET, MODFET, and MOST devices.

I. INTRODUCTION

REVIEWS of literature concerning noise can be found in [1]–[7]. Literature concerning failure mechanisms, degradation, and diagnostic tools for reliability assessment are found in [8]–[11]. Relatively little [12] was done on the relation between noise and failure mechanisms in devices, in spite of an exhaustive series of papers in conference proceedings on noise [1]–[7] and books and conference proceedings on quality enhancement of electronic devices [8]–[11].

Here, we shed some light on the relation between the noise of a device and its quality and reliability.

First, the different noise mechanisms are presented with special emphasis on those types which are very successful in being used as a diagnostic tool.

Then, we give experimental facts about the $1/f$ noise and the relation between $1/f$ noise and crystal quality. The $1/f$ noise sources are discussed in detail by Hooge in this issue [13]. The consequences of current constriction on the increase in local temperature and on $1/f$ noise in resistors is well understood. We explain why $1/f$ noise can be used as a diagnostic tool for: 1) electrical contacts and vias in VLSI circuits, and 2) thin conductive films or interconnects and why $1/f$ noise is a more sensitive parameter than the resistance, in detecting degradation by electromigration and stress.

The $1/f$ noise as a diagnostic tool in diode type devices will be reviewed. We discuss some results on zener diodes and avalanche photodiodes, solar cells, laser diodes, and bipolar

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transistors. A review of the literature on the low frequency noise in bipolar transistors is given by Kleinpenning in this issue [13].

Modern MESFET, MODFET, and MOS transistors with submicron channel lengths often suffer from the effects of series resistance; also for high-frequency devices (MODFET's) we propose low-frequency noise measurements as a sensitive technique to investigate quality and reliability.

There are also some pitfalls in the interpretation and comparison of noise results in devices. When the characteristics are studied to understand the mechanisms generating the noise we cannot claim that the noise is a diagnostic tool.

For example, research on the influence of ionizing irradiation on MOS transistors shows a shift in threshold voltage with irradiation mainly due to an increase in positive oxide charge. The effective gate voltage should be kept constant instead of the external gate voltage in investigations of the $1/f$ noise through the γ -irradiation process. Ignoring this explains the early misunderstandings about the $1/f$ noise increase and degradation in n-channel MOST's. A more detailed discussion by Fleetwood, Meisenheimer, and Scofield and by Vandamme, Li, and Rigaud about $1/f$ noise and parameter degradation, due to γ -irradiation or hot carrier effects in modern MOST's, can be found in this special issue [13].

II. TYPES OF NOISE IN VIEW OF SUITABILITY AS A DIAGNOSTIC TOOL

Here, we discuss the relevance of six types of noise as a diagnostic tool: 1) thermal noise, 2) shot noise, 3) burst noise, 4) generation-recombination noise, 5) $1/f$ -noise, and 6) $1/f^2$ -“noise.”

A. Thermal Noise

Semiconductors always display thermal noise caused by random motion of current carriers. The spontaneous fluctuations in voltage across a resistor due to the Brownian motion of carriers have a white spectrum given by

$$S_V = 4kTR \quad (1)$$

where k , T , and R are Boltzmann's constant, the absolute temperature and the resistance of the ohmic sample, respectively. The thermal noise of known resistors is often used to calibrate a noise measuring setup.

Only in a few cases this type of noise is used as a diagnostic tool: 1) to measure temperature in a hostile environment [14], 2) to measure the internal spreading resistance in the base of a bipolar transistor, and 3) to measure the quality of the heat contact between a film resistance and its substrate.

The thermal noise from a biased film is proportional to TR , where the film temperature T is larger than the substrate temperature T_s . The heat resistance is the ratio between the excess temperature ($\Delta T = T - T_s$) and the dissipated power in the film. Overly high values of the thermal resistance are a strong indication of delamination of the layer and hence an indication of early failures. Thus a strong increase in thermal noise under bias condition goes hand in hand with an increased risk of failures, due to ΔT -based degrading mechanisms.

B. Shot Noise

A second type of noise, always present in diode type devices is the shot noise. This noise is the result of the corpuscular nature of electricity and the random emission of charge carriers across a potential barrier. The spectrum of the current fluctuations is white and is proportional to the elementary charge q of the carriers and the average current I

$$S_I = 2qI. \quad (2)$$

At very low current levels, deviations from the proportionality between S_I and I are often used to detect parasitic shunt resistors across photodiodes. In high fields the onset of multiplication is easily detected where the increase in S_I is more than linear to current. Hence, shot noise is a well accepted diagnostic tool for quality evaluation in zener diodes [15] and photo and avalanche diodes [16]. This especially holds for long wavelength diodes made of III-V [17] and II-VI compounds [18] and for quality tests of Schottky barriers in MESFET's and MODFET's.

Due to the presence of high $1/f$ noise in modern submicron high-frequency devices, a noise measurement setup reaching at least 10 MHz has to be used to detect the onset of multiplication in avalanche photodiodes in the white part of the spectrum [17]. At lower frequencies burst noise, generation-recombination noise and $1/f$ noise can hide the shot noise. This low-frequency noise can also be used for the quality estimation for high frequency devices. From the results presented in [19], we observe that microwave oscillators show low-frequency AM and phase PM noise up to a corner frequency f_c , where it disappears in the white noise. From the results an empirical relation between the highest oscillating frequency f_0 of a device and f_c is $f_c \propto 5 \cdot 10^{-4} f_0$, with the oscillator frequency $5 \cdot 10^6 \text{ Hz} < f_0 < 10^{10} \text{ Hz}$. This is due to low frequency modulation of the gain element.

C. Burst Noise or RTS Noise

A third type of noise is the so-called "popcorn," burst, or random telegraph signal noise (RTS noise). This type of noise is par excellence an indicator of a single trap activity in a system with few free carriers. Such devices often have small dimensions and are submitted to high fields and current densities. Therefore they often degrade faster and at least

show a poor noise behavior. The current pulses in diodes, bipolar transistors or operational amplifiers at fixed operating conditions have a nearly fixed amplitude with typical durations of 1 s to 10^{-5} s. The amplitude can be as high as a few percent of the average current level. Burst noise is not Gaussian as are the other types of noise. The amplitude density distribution is mainly bimodal. This notorious type of noise was very popular as an object of study in the early seventies [20] and in the late eighties [21] with the advance of submicron devices. Burst noise, generation-recombination noise and $1/f$ noise are all fluctuations in the conductance. The less carriers in the system, the larger the relative resistance and voltage fluctuations will be. Hence, the fact that devices with burst noise have a higher $1/f$ noise content than devices without burst noise, is not an indication of a common physical origin of burst noise and $1/f$ noise. Kirton and Uren, however, tried to prove the contrary [21]. Strasilla and Strutt demonstrated that experimentally observed burst noise consists of a random telegraph signal superimposed on $1/f$ noise. The two processes are statistically independent [20]. RTS noise and burst noise are of the same variety although the term RTS is more reserved for rather clean submicron devices while the term burst noise was often used before 1980 for poorer-quality devices of larger size. In larger samples sub areas with increased current density and a single active trap are responsible for the two-level noise. Klempner [22] demonstrated that RTS noise only appears in devices with a small number of carriers, where one electron can be captured or emitted by a single active trap level. It was shown that RTS noise only overwhelms the ever-present $1/f$ noise, if there are less than 10^5 free carriers in the channel of a MOS transistor [22]. Thus RTS noise is a problem typical for submicron MOST's or bipolar devices with crystallographic damage in sensitive areas [23]. Traps too far away from the Fermi level are either full or empty on average and are inactive. Therefore RTS noise is temperature and bias dependent.

The voltage noise spectrum of RTS fluctuations is due to number fluctuations of carriers. The spectrum of a pure RTS signal is Lorentzian and is given by the following in ohmic devices:

$$\frac{S_N}{N^2} = \frac{S_I}{I^2} = \frac{S_v}{V^2} = K \frac{4\tau_p}{1 + (2\pi f\tau_p)^2} \quad (3)$$

where τ_p is the relaxation time in the correlation function, with $1/\tau_p = 1/\tau_c + 1/\tau_e$ and where τ_c and τ_e are the average capture and emission times, respectively, and K equals $\overline{\Delta N^2}/N^2$. Generally $\overline{\Delta N^2} \leq 1/4$ and for the special case $\tau_c = \tau_e$ we find $\overline{\Delta N^2} = 1/4$. For a single-electron switching process we find for K that in general

$$K = \frac{1}{N^2} \frac{\tau_p}{\tau_c + \tau_e} \quad (4)$$

which immediately explains why RTS noise is a typical problem in submicron devices, but it has been reported in JFET's with active volumes in excess of 1000 cubic microns. Now we will explain why.

- 1) As was already mentioned earlier in the text RTS noise is nothing else than a conductivity fluctuation. For conductivity fluctuations holds in general that, although the

noise source can be distributed uniformly in the sample, their effect on the voltage or current fluctuations at the terminals can be quite different. Areas with a current density far above the average are very effective in translating the local conductivity fluctuations into voltage or current fluctuations at terminals as is shown in chapter IV, (13). This holds for all types of noise provided they are caused by conductivity fluctuations. For inhomogeneous current densities a reduced effective number of carriers N_{eff} has to be introduced in (3) and (4).

- 2) Furthermore, the strength of a conductivity noise source of the number fluctuations variety strongly depends on the position of the Fermi-level. A trap level far below or far above the Fermi-level is either full or empty and does not show a strong possibility to modulate the number of free carriers in the sample.

For the above mentioned reasons RTS noise can also be observed in large samples and can be strongly dependent on gate and drain voltage in junction FET's and MOS- and MODFET's. Kandiah *et al.* [24], [25] were very successful in using RTS noise as a screen for bad JFET's.

D. Generation-Recombination Noise

Generation-recombination noise (g - r noise) is a fluctuation in the conduction, and like burst noise, is due to number fluctuations of carriers. The amplitude density distribution is Gaussian and the spectrum for simple transitions between a band and traps at one energy level is given by a Lorentzian

$$\frac{S_{\Delta N}(f)}{N^2} = \frac{\overline{\Delta N^2}}{N^2} \left[\frac{4\tau}{1 + (2\pi f\tau)^2} \right] \quad (5)$$

where $\overline{\Delta N^2}$ is the variance of the fluctuating number of charge carriers and τ is the relaxation time of carriers. If $\overline{\Delta N^2} < N$ the variance is called sub-Poissonian. What often holds for semiconductors is that $\overline{\Delta N^2} = N_t$ being the number of effective traps for $1 < N_t < N$ and otherwise $\overline{\Delta N^2} = N$ for $N < N_t$.

Generation-recombination is a well understood phenomenon [26]. Although traps cannot always be avoided, a device can be "free" from g - r noise in a certain temperature range due to the fact that the energy level is far below or above the Fermi level, and hence communication with such traps becomes negligible. Generation-recombination noise is often absent in high-quality silicon devices, but not yet in heterostructures and compound semiconductors where lattice defects are often a problem.

Generation-recombination noise spectroscopy of trap centers in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and other compounds is a powerful diagnostic tool in modern devices, as can be found for example in [27]–[29]. In poor samples the g - r noise is generated at the contacts or at the surface. In better samples the dominant conductance noise source is in the bulk and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ samples with $x \leq 0.2$ have no g - r noise at all at 300 K [30].

So, generation-recombination noise is a powerful diagnostic tool to study trap center in III-V and II-VI compounds semiconductors. Its results correlate very well with the outcomes of classical techniques known by the acronym deep level transient spectroscopy (DLTS). Generation recombination noise can be

overwhelmed by another type of conductance fluctuation the so-called $1/f$ noise.

E. $1/f$ Noise

A fifth type of noise is the $1/f$ noise. The spectra of these conductance fluctuations are inversely proportional to frequency in a very wide range. In general resistivity fluctuations can have two origins: 1) fluctuations in the number of free charge carriers like in RTS and g - r noise, or 2) fluctuation in the mobility. At this time there is no definite decision on which of the two models is correct for the $1/f$ noise. In fact it seems that both origins of $1/f$ noise exist (see also the contribution of Hooge [13] and of Vandamme, Li, and Rigaud [13]).

It is quite possible to use the results of a measurement of $1/f$ noise as a measure of the quality of a semiconductor material or device, although we do not know much of the origin and nature of $1/f$ noise [12], [31].

In homogeneous semiconductors we can characterize the $1/f$ noise by a parameter α according to

$$\frac{S_R}{R^2} = \frac{\alpha}{fN} \quad (6)$$

where S_R is the spectral power density of the noise in the resistance R , N is the total number of free charge carriers, and f is the measuring frequency. The parameter α then is the contribution of one electron to the relative noise at 1 Hz, assuming that the N electrons are uncorrelated noise sources [31].

In situations more complicated than a homogeneous crystal, we use (6) for volume elements, and using a proper integration procedure we find the magnitude of the $1/f$ noise in currents and voltages. Point contacts, multi-spot contacts, diodes, MOST's, and other devices have been treated in this way [31]. The noise of devices and complicated structures is then expressed in local values of α . It has been found that α is not a constant, but that α depends on the prevailing type of scattering of the electrons and—what is important for us here—on the perfection of the crystal lattice.

In recent years much progress has been made on this point, since we now can investigate perfect layers grown by molecular beam epitaxy. After damaging the crystal lattice in a systematic way, we can see what has happened to the α values.

There is no simple model for the $1/f$ mobility fluctuations. We know that the noise is in the lattice scattering and that it can be expressed by the relation

$$\frac{S_{\mu_{\text{latt}}}}{\mu_{\text{latt}}^2} = \frac{\alpha_{\text{latt}}}{fN}. \quad (7)$$

If there is a mixture of scattering mechanisms, e.g., lattice scattering and impurity scattering, Mathiessen's rule holds

$$\frac{1}{\mu} = \frac{1}{\mu_{\text{latt}}} + \frac{1}{\mu_{\text{imp}}}. \quad (8)$$

From (6)–(8) there follows [31], [32]

$$\alpha = \left(\frac{\mu}{\mu_{\text{latt}}} \right)^2 \alpha_{\text{latt}}. \quad (9)$$

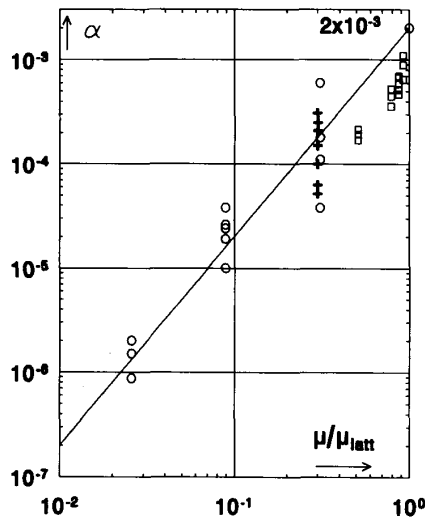


Fig. 1. Experimental values of α versus μ/μ_{latt} at 300 K. Circles (\circ) denote p-type Ge samples with resistivities in the range of $4.5 \cdot 10^{-4} \Omega\text{cm} \leq \rho \leq 50 \Omega\text{cm}$. Crosses (+) denote thick samples of n-type GaAs with $\rho = 2.7 \cdot 10^{-3} \Omega\text{cm}$ [32]. Squares (\square) denote MBE grown GaAs layers with thickness between $3.2 \mu\text{m}$ and $10 \mu\text{m}$ and electron concentration between $2.5 \cdot 10^{14} \text{cm}^{-3} \leq n \leq 10^{17} \text{cm}^{-3}$ [33]. Solid line is according to (9).

When we study a series of similar samples all made by the same crystal growth technology but with different doping levels—and therefore different contributions of impurity scattering—we can plot the α -values experimentally found versus the mobilities μ . According to (9) we find a quadratic dependence from which α_{latt} can be derived by extrapolation. In Fig. 1 Ge, GaAs samples and MBE-grown GaAs samples are grouped together [32], [33]. Further evidence for the reduction factor $(\mu/\mu_{\text{latt}})^2$ was found by Palenskis and Shoblitskas [34]. They showed that the reduction in α proportional to $(\mu/\mu_{\text{latt}})^2$ is independent of the way in which the ratio (μ/μ_{latt}) was realised either with the help of temperature $77 \text{ K} < T < 400 \text{ K}$ or by changing the amount of impurities. In their experiments α_{latt} was $9 \cdot 10^{-4}$ for p-type Si and $2 \cdot 10^{-3}$ for n-type in the whole temperature range.

The problem of ΔN or $\Delta\mu$ types of $1/f$ noise we now see as follows. In semiconductors there always is a mobility noise. In perfect material α_{latt} has a value of 10^{-4} at most at room temperature. The value of α can be lowered by other scattering mechanisms according to (9). On the top of the ubiquitous lattice scattering noise, there may be other $1/f$ noise mechanisms like McWhorter's number fluctuations. Hooge and Tacano gave a survey on the noise mechanisms in GaAs [35]. In this issue Hooge [13] shows that impurity scattering does not show appreciable $1/f$ noise.

F. $1/f^2$ -“Noise”

In contrast to burst, g - r and $1/f$ noise, where the current only serves to measure the already existing conductance noise [31], the so-called $1/f^2$ “noise” is due to a dc-current induced resistance drift or resistance fluctuations. There is a threshold current density and a threshold temperature for observing $1/f^2$ noise. Above the threshold current density of about $2 \cdot 10^6$

A cm^{-2} for Al-based lines, the current stimulates electromigration, resistance drift, and fluctuations. Thus the noise voltage spectrum is no longer proportional to I^2 as in burst, g - r and $1/f$ noise. Above $6 \cdot 10^6 \text{ cm}^{-2}$ Al films generally burn out. From the perspective of noise as a diagnostic tool, $1/f^2$ “noise” is extremely useful in studies on electromigration [36]–[43], because the electromigration mechanism itself gives rise to the noise. The $1/f^2$ noise measurement provides a means for quick and accurate measuring of electromigration activation energies [38], [41], [42]. An empirical expression for the voltage noise spectrum is

$$S_v(f) = \frac{I^\beta C}{f^\gamma T} \exp(-E_a/kT) \quad (10)$$

where $\beta \geq 3$ and $\gamma \geq 2$, C a parameter depending on geometry and technology and E_a is the electromigration activation energy from noise measurements, which is close to the activation energy from accelerated life test resulting in the median time to failure (MTF) and the time to failure (TTF) of the film.

The lifetime tests are performed on a large number of samples, because MTF is defined as the time of 50% failure of the group made under identical conditions. These lifetime tests are time consuming and destructive. The electromigration damage rate $(\text{TTF})^{-1}$ in Ti W/Al [36] and W/Al-Cu metallizations [42] has a similar dependence on T and I as is given by (10). This suggests that there is a close relationship between $1/f^2$ noise and electromigration damage. A review of literature on low-frequency noise measurements for electromigration studies can be found in [42]. A model relating $1/f^\gamma$ noise (with $\gamma \approx 2$) to electromigration mechanisms was developed [41], [42], based on electron mobility fluctuations due to scattering on vacancies migrating along the grain boundaries. When $\gamma \rightarrow 2$, the value of C in (10) tends to become infinite [41] which is quite unrealistic.

In some models the diffusion of vacancies at the grain boundaries is put forward to explain not only the $1/f^\gamma$ noise but also the $1/f$ noise. One must realize that, although the mean time to failure of electromigration hardened metallization can be at least ten times higher than in Al, the $1/f$ noise in both types of layer at low current densities is about the same.

The above-mentioned techniques to investigate electromigration in Al based films are also indicated by the acronym spectral analysis of resistance fluctuations (SARF) and the $1/f^\gamma$ noise is also called EM (electromigration) noise [43]. From their results an exponential dependence follows between C in (10) and the grain size like $C \propto e^{-bD}$ with b about $3.2 \mu\text{m}^{-1}$ and D the grain size. The Al/Si(1%) films were deposited at five different substrate temperatures resulting in different grain sizes [43].

In order to avoid a $1/f^2$ spectrum due to simple drift [39], two films are investigated at the same time in a bridge configuration [44] assuming the same drift in both samples. Chen [44] discusses the different roles played by the thermal, $1/f$ and $1/f^2$ noise in reliability testing of Al-based thin films and shows that wafer level testing is possible.

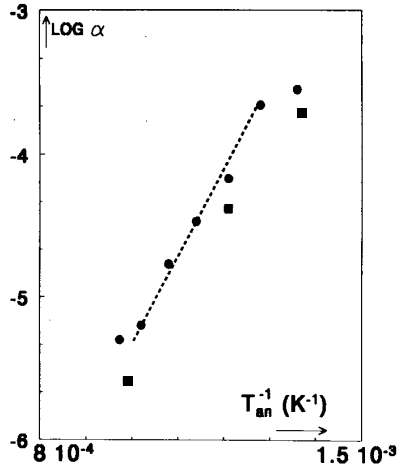


Fig. 2. α versus the reciprocal anneal temperature in boron implanted Si [45]. The dots (\bullet) are obtained at $T = 300$ K the squares (\blacksquare) indicate results at $T = 77$ K. The dotted line through the results at $T = 120$ K show the proportionality $\alpha \propto e^{\frac{\Delta E}{kT_{an}}}$ with $\Delta E = 1.1$ eV.

III. $1/f$ NOISE AND CRYSTAL QUALITY

A. Damaged Material

The crystal lattice can be damaged by mechanical stress or by irradiation with protons or other ions. As a result α increases considerably whereas the mobility changes by about 10%. The conductivity fluctuations in 1 MeV boron-implanted layers in silicon have been investigated at 300 K and 120 K with the anneal temperature as a parameter. Annealing of implants causes a decrease in the $1/f$ noise parameter α . The α -value is proportional to $e^{\frac{\Delta E}{kT_{an}}}$ with T_{an} the anneal temperature and $\Delta E = 1.1$ eV; an activation energy corresponding to that for auto-diffusion of atoms in silicon.

From the noise study, the optimum anneal temperature to find a tradeoff between a decreasing $1/f$ noise and an increasing generation-recombination noise with increasing anneal temperature is obtained at [45]

$$T_{an} \approx 0.6 T_m(K) \quad (11)$$

with T_m the melting temperature in Kelvin.

The experimental α -values [45] as a function of the reciprocal anneal temperature are shown in Fig. 2 with dots (\bullet) for samples at 300 K and squares (\blacksquare) for samples at 120 K. The observed ratio between the highest and the lowest mobility in the annealed samples is only 1.3. From these results it follows that α_{latt} in (9) is defect dependent. The optimum noise figure in GaAs devices was attributed to the higher epilayer quality, grown at an optimum temperature given by (11), see references mentioned in [45].

Recent studies [46] on undamaged epitaxial GaAs showed that there α_{latt} can be expressed as

$$\alpha_{latt} = 0.1 \exp \left[\frac{-0.13 \text{ eV}}{kT} \right] + 7 \cdot 10^{-5}. \quad (12)$$

This expression suggests two types of mobility noise. One is temperature dependent with an activation energy of 0.13

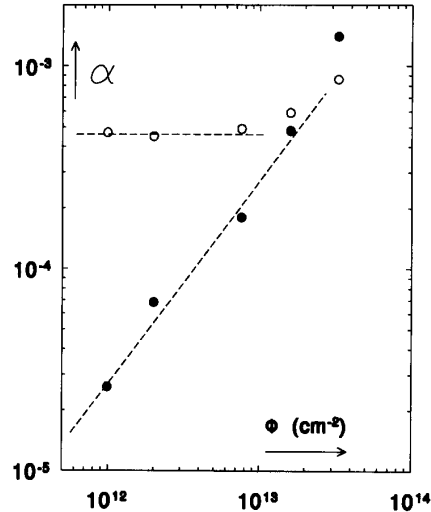


Fig. 3. The $1/f$ noise in proton irradiated n -GaAs [47]. α -values at $T = 78$ K (\bullet) and at $T = 295$ K (\circ) versus irradiation doses ϕ . The solid line shows proportionality between the low temperature α -values and proton irradiation dose ϕ . The broken line shows the dose-independent α -values at room temperature. (L. Ren, "Intrinsic and extrinsic $1/f$ noise source in proton-irradiated n -GaAs epitaxial layers," *J. Appl. Phys.*, vol. 74, pp. 4534-4539, 1993).

eV. At lower temperatures the other one is found, which is temperature independent.

Fig. 3 shows the results of irradiation with protons [47]. The exponential branch in α versus $1/T$ is not influenced. The lower-temperature branch increases proportionally with irradiation dose. The damage caused by the proton irradiation induced $1/f$ noise sources. In this case it is certain that the induced noise is not due to number fluctuations. Both high and low-temperature noise are mobility noise, as follows from plots of α versus μ , analogous to Fig. 1.

A low α -value does not necessarily mean a high crystal quality, but very often it goes hand in hand with a low μ value in the material. However, a low α_{latt} -value certainly means high crystal quality.

B. Bulk and Surface Contribution

The controversy over the bulk or surface origin of $1/f$ noise has a long history [48]. Although there is broad experimental evidence for the bulk origin of $1/f$ noise in metals and semiconductors [31], there are some experimental results that point to a strong surface influence. Invoking the role of the interface has always been very popular in describing the $1/f$ noise in MOS transistors. Experimental results presented in Figs. 2 and 3 indicate that α -values can be associated with the number of crystal defects in the bulk [45], [47] and the proportionality between $1/f$ noise and oxide-trap density in MOST's can be associated with the quality of the Si-SiO₂ interface [49]. The spatial distribution of the $1/f$ noise sources in an n -type resistor surrounded by a p -well has been investigated [48]. By depleting the Si-SiO₂ interface region with a negative gate voltage, the bulk $1/f$ noise sources are observed and characterized by α_b . Under a positive gate

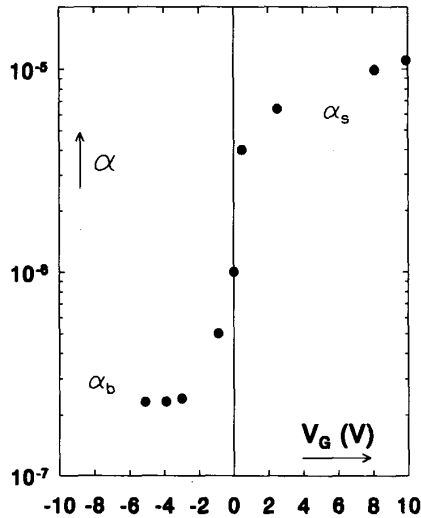


Fig. 4. The $1/f$ noise parameter α versus the gate voltage from a n -Si [48] gated resistor, under conditions ranging from depletion to accumulation at 300 K. α_b is the bulk value and α_s is the surface value. (See [48]).

voltage, accumulation is reached and the $1/f$ noise sources close to the Si-SiO₂ interface are characterized by α_s . With a positive voltage we are creating an accumulation layer and the current is at the Si-SiO₂ interface. By applying negative gate voltages, we have shifted the conduction path away from the surface into the bulk. Fig. 4 shows the dependence of the $1/f$ noise parameter α on the gate voltage.

The α -values in the bulk are about $\alpha_b \approx 2 \cdot 10^{-7}$ and the surface values $\alpha_s \approx 10^{-5}$. We suggest that the $1/f$ noise sources close to the interface are higher due to higher crystal defect density. The $1/f$ noise can still be described by a bulk model (6), however, with two values for the $1/f$ noise parameters $\alpha_s \approx 10^{-5}$ and $\alpha_b \approx 2 \cdot 10^{-7}$ depending on which conduction path is dominant.

Equation (12) suggests an activation-energy dependent part in mobility noise for semiconductors with $E_a = 0.13$ eV. This type of noise, that depends on temperature with E_a in the range of 0.1–0.4 eV, was also observed in metal films with a high concentration of mobile defects. These energy values correspond to the energy required for a vacancy creation by breaking 1 or 2 lattice bonds [50]–[52].

The frequently observed relation between surface states and $1/f$ noise in MOST's [49] can be interpreted in terms of bulk $1/f$ noise due to mobility fluctuations. That is if an increased number of surface states goes hand in hand with increased Si-SiO₂ interface roughness, or an increased defect density in the region just below the SiO₂. Then experimental results that are usually explained by the McWhorter model can then also be explained by (6) with different local α values.

IV. $1/f$ NOISE AND RELIABILITY

Amerasekera and Campbell [8] systematically describe the causes, the effects and the prevention of different degrading mechanisms in their book *Failure Mechanisms in Semiconductor Devices*. Dislocations and electromigration in metallization

affect device reliability and have been identified as the main source of device failure. Here, we explain why the ever-present $1/f$ noise can be used as a diagnostic tool to detect early failures related to current density. Measurement of the contact noise can provide a characterization of the contact. It is even possible to calculate contacts' details [53], [54] from contact resistance and noise measurements.

A. Current Crowding and $1/f$ Noise

For ohmic samples with nonuniform fields N , in (1) has to be replaced by the smaller value N_{eff} like [31], [53], [55]

$$N_{\text{eff}} = n \left[\int_{\Omega} J^2 d\Omega \right]^2 \left[\int J^4 d\Omega \right]^{-1} = n \Omega_{\text{eff}} \quad (13)$$

where n is the concentration of free charge carriers, J the current density in the sample, Ω the sample volume, and N_{eff} and Ω_{eff} are the effective number and volume located in an area with higher current density. For a uniform current density in the sample (J constant) (13) results in the largest values for $N_{\text{eff}} = N$ and $\Omega_{\text{eff}} = \Omega$. Current constriction will cause high local current densities and hence small effective volumes and a high $1/f$ noise (see (6) and (13)).

Contacts are notorious for their high $1/f$ noise. Current crowding is coupled to increased $1/f$ noise and increased local temperature. Therefore, a strong correlation must be expected between $1/f$ noise and temperature-based degrading of the device.

B. Contact Noise as a Diagnostic Tool

A single circular contact with radius a , between two conducting spheres without interface complications, has a contact resistance R and effective volume Ω_{eff} given by [31], [53]–[56]

$$R \cong \frac{\rho}{\pi a} \quad (14)$$

$$\Omega_{\text{eff}} = 20\pi a^3. \quad (15)$$

Contacts between crossed metal bars have been investigated to check (14) and (15). By increasing the pressure on the bars, one increases the contact spot radius a , and reduces the contact resistance R and the $1/f$ noise S_R . The experimental results are shown in Fig. 5 as a C versus R diagram with $C \equiv f S_R / R^2$, which is the relative $1/f$ noise in the contact resistance at $f = 1$ Hz. For complication-free contacts we expect $S_R / R^2 \propto 1 / \Omega_{\text{eff}} \propto 1 / a^3 \propto R^3$ and, indeed, for manganin and constantan we observe in Fig. 5 $C \propto R^3$ which is in support of (14) and (15). This proves that constriction dominated contact noise is nothing else than normal bulk $1/f$ noise. The above (14) and (15) can be valid for vias between two interconnect layers with strong inhomogeneous current densities. The calculated noise $S_R = R^2 \alpha / n \Omega_{\text{eff}} f$ using (14) and (15) is the minimum amount of $1/f$ noise that can be expected from a complication-free contact. Therefore, contact noise is a diagnostic tool for tracing contact complications.

Now we will investigate contacts affected by uniform interfaces or punched films. They have a dependence between the contact noise and contact resistance, which is different from

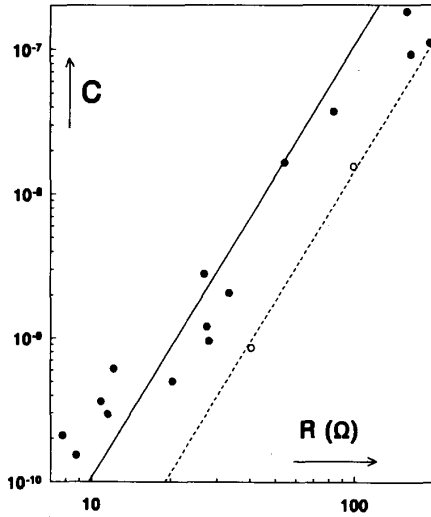


Fig. 5. Normalized contact noise $C = fS_R/R^2$ as a function of the contact resistance. ● stands for manganin, and ○ stands for constantan [56]. Lines are drawn using [56] $C = \alpha\pi^2 R^3/20n\rho^3$. Solid line with $\alpha = 6 \cdot 10^{-4}$ is for manganin alloy, while the dotted line with $\alpha = 1.2 \cdot 10^{-4}$ is for constantan alloy. (See [56]).

the dependence of simple constriction-dominated contacts. This can be easily studied from a set of metal semiconductor contacts with different contact radii.

For a circular interface-dominated contact with radius a , we find that for R and that for Ω_{eff} holds [57]

$$R = \frac{\rho_i t_i}{\pi a^2} = \frac{\rho_c}{\pi a^2} \quad (16)$$

$$\Omega_{\text{eff}} = \pi a^2 t_i \quad (17)$$

where ρ_i and t_i are the interface resistivity and thickness and the product $\rho_i t_i$ is often represented by the contact resistivity ρ_c (in Ωcm^2). This results in an expected noise dependence

$$\frac{S_R}{R^2} \propto \frac{1}{\Omega_{\text{eff}}} \propto \frac{1}{a^2} \propto R \quad (18)$$

hence $S_R \propto R^3$ or $C \propto R$.

The squares ■ in Fig. 6 show contact noise at $f = 1$ Hz between a metal and semiconductor [58]. The contact needs improvement, because we observe $S_R \propto R^3$ instead of $S_R \propto R^5$, which is expected for a complication-free contact, dominated by a simple current constriction.

For multi-spot contacts with k spots with radii a in parallel [54], [59], we expect that for R and Ω_{eff} holds

$$R \propto \frac{\rho}{ka} \quad (19)$$

$$\Omega_{\text{eff}} \propto ka^3 \quad (20)$$

with ρ the conductivity of the bulk. The interface does not play a role in this type of contact. Keeping the number of spot radii k constant for all contacts and changing a , we expect that for the relative contact noise holds

$$\frac{S_R}{R^2} \propto \frac{1}{\Omega_{\text{eff}}} \propto R^3 \quad (21)$$

and hence $S_R \propto R^5$.

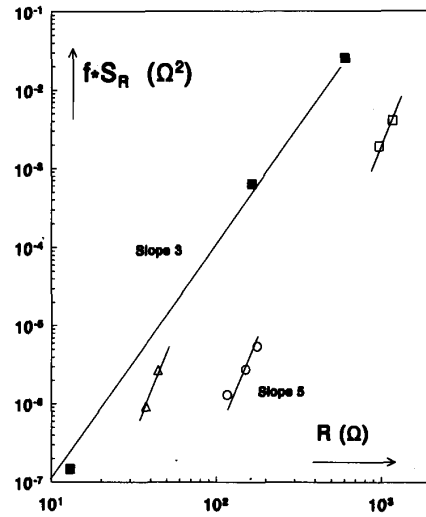


Fig. 6. The contact resistance noise at 1 Hz, fS_R versus contact resistance R of circular silver contact on Cu_xS layers are depicted by ■ [58]. The results denoted by △, ○, and □ are from the movable contact (wiper) of potentiometers on three different track resistivities [60].

This constriction dominated contact behavior can be observed, for example, in contact noise of the movable contact of different potentiometers [60], as is indicated in Fig. 6 by the symbols △, ○, and □. Three different track resistivities are investigated here and the results of the contact noise of the wiper on each of them is shown by △, ○, and □, respectively. The contact resistance of the wiper on the three different tracks, scales with the track-resistivity which proves that the interface is not dominant. We observe $S_R \propto R^5$, instead of $S_R \propto R^3$, for interface complicated contacts which are represented by ■. Both trends, notably $R \propto \rho$ and $S_R \propto R^5$, indicate a constriction dominated contact in view of (19) and (21) with constant number k of spots in parallel and variable radii a .

There is a growing interest in III-V and II-VI binary, ternary and quaternary semiconductor compounds. Making low-noise contacts is not trivial on GaAlAs or CdHgTe compounds, for example. Noise analysis helps to improve contact technology and reliability. In the early days even low-noise contacts on n -GaAs were difficult to make [59]. Alloying of the AuSi film deposited on GaAs at 450°C and higher, causes the formation of globules, thus creating a multi-spot contact area. Continuous ohmic contacts were obtained by alloying the AuSi film in H_2 at 425°C. The patchiness of contacts can be determined from measurements of $1/f$ noise and contact resistance [59].

The native oxide layers on semiconductors, the anneal temperature [59], [61] and the composition of the forming gas [62] are very critical in obtaining low-noise ohmic contacts. Fig. 7 shows the strong difference in noise for only a small difference in contact resistance on p-type GaSb samples [62].

The physical bond formed at contact window on the semiconductor surface is ideally formed by the exchange of a few atoms from each element which makes it strong. An uncontrolled exchange of Al into silicon can cause spiking and short circuit. Diffusion of Si into the metal results in voiding

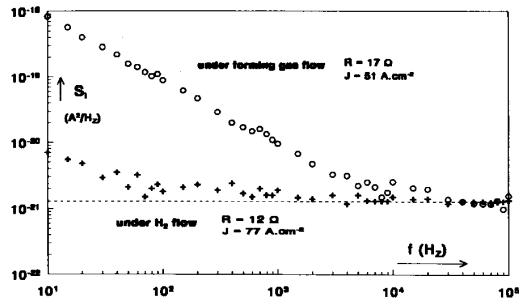


Fig. 7. Noise spectra for p-type GaSb ohmic contacts annealed under H_2 flow or under forming gas flow [62]. The relative $1/f$ contact noise S_R/R^2 at 10 Hz is improved by a factor of about 300, the resistance dropped from 17 Ω to 12 Ω .

at the contact and open circuits. This results in changes in the ohmic resistance and stronger changes in $1/f$ noise. For that reason contact noise can be used as a diagnostic tool.

Miniaturization of the interconnections and contact windows in a VLSI chip increases resistance of the interconnections and contacts. Mechanisms affecting the reliability of the metallization such as electromigration, mechanical stress relaxation, and contact migration, become more pronounced in small dimensions. Testing for these failures with $1/f$ noise is nondestructive and with $1/f^2$ noise it is less destructive than aging experiments.

C. Current-Induced Degradation

Degradation by electromigration in thin conducting films often goes hand in hand with the creation of voids or kinks (the so-called mouse bites) and an increase of current density around these voids or kinks. The general equations for resistance and the $1/f$ noise in resistance are [63]

$$R = \frac{1}{l^2} \int \rho J^2 dA \quad (22)$$

$$S_R = \frac{1}{l^4} \int \frac{\alpha \rho^2}{nf} J^4 dA \quad (23)$$

where I is the current passed through the film. For nonhomogeneous current densities the value N in (6) has to be replaced by a reduced value N_{eff} given by (13). For films a two-dimensional treatment is proposed, where ρ is the sheet resistance (Ω), J (Acm^{-1}) the two-dimensional current density, dA (cm^2) an area element and n (cm^{-2}) the free charge carrier concentration. Based on simplified assumptions [64] for the current density around the voids, we solved the integrals in (22) and (23). The results of the calculations are shown as full lines in Fig. 8 for two different width-length ratios of the films. The resistance and the noise of a failure free sample are denoted by R_0 and S_{R0} .

Fig. 8 shows the increase in resistance and noise due to one void with increasing diameter. The resistance and noise of the degraded lines with two different W/l ratios are normalized on the values of an undamaged film. The experimental results denoted by \square and \blacksquare obtained at current densities resulting in a pure $1/f$ spectrum are in good agreement with the calculations. For an increase in resistance of about 15%,

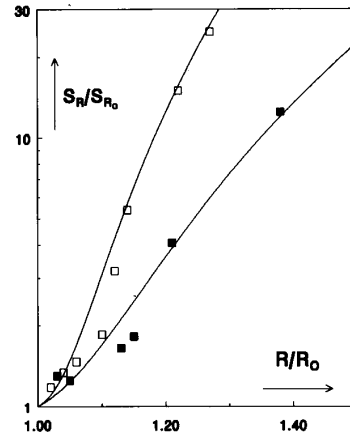


Fig. 8. $1/f$ noise in a film damaged by one void [64]. The relative increase in $1/f$ noise versus relative increase in resistance due to an increasing void diameter. Solid lines are calculated from a simple model [64]. Experimental results for a width-length ratio of 10/100 are denoted by \blacksquare and 10/300 are denoted by \square .

we observe a noise increase by factor 10, which explains why resistance noise measurements are more sensitive than resistance measurements. The relative increase in $1/f$ noise can be used as a failure analysis test applicable to LSI Al interconnects and thin films resistors.

V. $1/f$ NOISE IN DIODE TYPE DEVICES AND RELIABILITY

A. Solar Cells, Lasers, and Avalanche Photodiodes

Kleinpenning's model [65] for the current fluctuations in a forward-biased diode without complications, can be expressed as follows for a long diode at a medium current range

$$S_I \cong \frac{\alpha q I}{\tau f} \quad (24)$$

with I the forward current, q the elementary charge and τ the dominant recombination lifetime outside or inside the depletion layer, depending on the ideality factor. For a diode with series resistance, a proportionality $S_I \propto I^2/f$ is to be expected.

Correlation between $1/f$ noise and diode degradation can be expected for the following reasons. Inhomogeneities in the junction or poor electrical contact of a large area solar cell will result in a reduced lifetime for the device. In both cases the observed noise will be much larger than given by (24). Spots at the junction with reduced carrier lifetime result in an increase of local current density and an increase of local temperature. For a large area device, this weak spot is hardly seen in the saturation current of a dark solar cell, but is more pronounced in the current fluctuations [66]. Fig. 9 shows the $1/f$ noise of a dark solar cell with an area of 800 mm^2 . Using (24) and an observed value of τ_j for recombination in the depletion region too high an α value of $5 \cdot 10^{-2}$ is observed. This points to inhomogeneities in the junction and a poor crystal quality. Problems with series resistance in solar cells have been observed by [67].

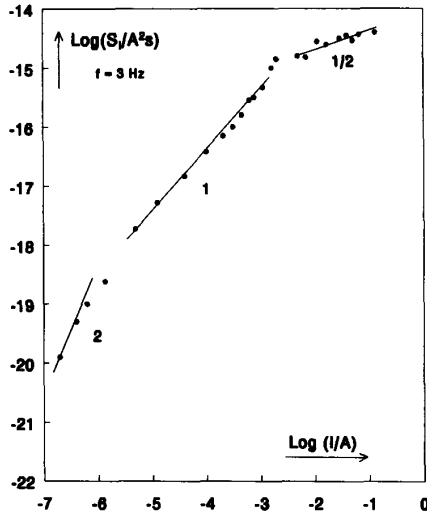


Fig. 9. The observed $1/f$ noise S_I at $f = 3$ Hz as a function of forward current I from a n^+p silicon solar cell [66]. The ideality factor and the recombination time constant in the junction is $\eta = 2$ and $\tau = 4 \cdot 10^{-9}$ s for 10^{-5} A $< I < 10^{-3}$ A. (L. K. J. Vandamme, R. Alabedra, and M. Zommiti, "1/f Noise as a reliability estimation for solar cells," *Solid-St. Electron.*, vol. 26, pp. 671-674, 1983.)

In short diodes the relation for S_I contains a factor with the diffusion coefficient, the contact or surface recombination velocity s (cm/s) and the base-length w of the diode which is often reverse bias dependent [65], [69].

$$S_I = \frac{\alpha q I D}{f w^2} \ln \left[\frac{s + D/W}{s \exp(-qV/kT) + D/w} \right] \quad (25)$$

where $W < L_p$, the hole diffusion length in a p^+n diode, and D is the diffusion coefficient. The local value of s at the diode edges can change and hence the $1/f$ noise. The value of s makes the link between quality of passivation of diodes and the amount of expected $1/f$ noise by (25).

From the deviations of the shot noise at high frequencies, we observed the following in reverse-biased (avalanche) photodiodes: 1) at low bias, shunt resistors across the diode due to passivation problems, 2) at higher reverse bias, the onset of multiplication and its contribution to the noise. In reverse bias the multiplication process does not show $1/f$ noise [68], [69]. From the $1/f$ noise in forward bias, we calculated the α value in different areas and the noisiness of the series resistance [68].

Degradation in laser diodes can stem from an increase in nonradiative recombination in areas with strain and dislocations. This results in a decrease of spontaneous emission and hence in an increase in threshold current and a decrease in external quantum efficiency. The $1/f$ noise parameter α increases with the concentration of dislocations and S_I is proportional to α and inversely proportional to the carrier lifetime. From this degradation model, we can expect high $1/f$ noise in devices with a spoiled lifetime [70], due to extra nonradiative recombination.

Laser diodes can suffer from contact degradation, especially if it goes hand in hand with increased thermal resistance due to loss of contacts. Above threshold, a strong correlation can be

expected between the experimentally observed electrical noise and the contact degradation.

It is experimentally demonstrated that the FM noise resulting in increased spectral linewidth increases during device degradation, and $1/f$ noise correlates with laser degradation [71].

B. Bipolar Transistors

How to distinguish the different $1/f$ noise source contributions is discussed by Kleinpenning in this issue [13]. Konczakowska *et al.* have shown the strong correlation between bipolar device lifetime and the $1/f$ noise. They used $1/f$ noise as a lifetime estimator [72]–[75]. They divide transistors into two groups; one having the natural (essential) $1/f$ noise, while the other group is mismanufactured due to bad bonding and shows redundant noise besides natural noise. This applies not merely to bipolar transistors but to any bonded device.

VI. $1/f$ NOISE IN FET TYPE DEVICES

A. MODFET's and MOST's With Series Resistance Problems

The $1/f$ noise in the gate current can be used as a diagnostic tool to detect device failure in MESFET's and MODFET's [76]. Short-channel HEMT-type GaAs FET's under low gate voltage show considerable contributions to the $1/f$ noise from the parasitic resistance in series with the gate-voltage-dependent channel resistance. The relative $1/f$ noise in MODFET's, S_I/I^2 , versus the effective gate voltage can be used as a tool for diagnosing the lack of device quality. The relative $1/f$ noise in the current at $f = 20$ Hz; S_I/I^2 as a function of the effective gate voltage V_G^* is shown in Fig. 10. Three different regions are observed: $S_I/I^2 \propto V_G^{*m}$ with $m = -1, -3$ and 0 for the MODFET represented by the symbol \blacktriangledown . For a MOS transistor with reduced quality and reliability, we observed $m = 2$ and the results are indicated by \blacktriangle . This can be explained by taking the noise contribution into account from the channel resistance R_{ch} varying with V_G and a constant contribution due to the series resistance R_s . The total resistance $R = R_{ch} + R_s$. The two contributions are uncorrelated, so for the noise S_R we find

$$S_R = S_{R_{ch}} + S_{R_s}. \quad (26)$$

Starting from (6) and, considering that in first approximation for MODFET's and MOST's holds: $N \propto V_G^*$ and $R_{ch} \propto V_G^{*-1}$ and $R_s \propto V_G^{*0}$, then we find $S_{R_{ch}} \propto V_G^{-3}$ and for $S_{R_s} \propto V_G^0$. Four typical situations are possible [77] for the relative $1/f$ noise $C = fS_I/I^2$ versus V_G^* starting from small values up to high V_G^* values:

- $R_{ch} > R_s$ and $S_{R_{ch}} > S_{R_s}$ results in $C \propto V_G^{*-1}$ ($m = -1$)
- $R_{ch} > R_s$ and $S_{R_s} > S_{R_{ch}}$ results in $C \propto V_G^{*2}$ ($m = 2$)
- $R_s > R_{ch}$ and $S_{R_{ch}} > S_{R_s}$ results in $C \propto V_G^{*-3}$ ($m = -3$)
- $R_s > R_{ch}$ and $S_{R_s} > S_{R_{ch}}$ results in $C \propto V_G^{*0}$ ($m = 0$).

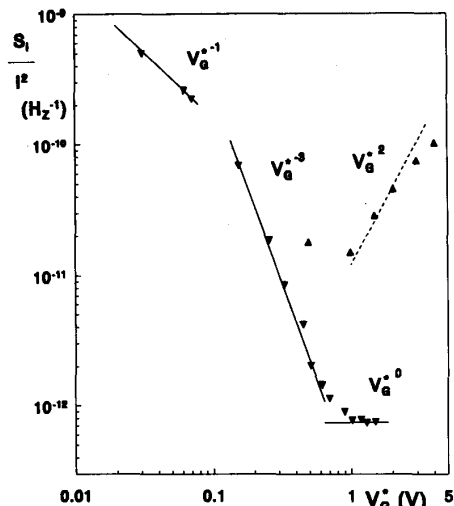


Fig. 10. The relative $1/f$ noise in the drain current S_1/I^2 at $f = 20$ Hz versus the effective gate voltage V_G^* for Sony MODFET with gate length $0.5 \mu\text{m}$ [77] is represented by the symbol \blacktriangledown . High effective gate voltage in the MODFET means low gate voltage. S_1/I^2 at $f = 20$ Hz versus V_G^* is shown by the symbol \blacktriangle from an edgeless (concentric) n-channel MOS transistor [78]. For the MOS transistor a high effective gate voltage means high gate voltage.

Three typical situations, $m = -1$, $m = -3$ and $m = 0$ can be observed in Fig. 10 for MODFET's [77], the situation $m = 2$ is observed in a MOS transistor with noisy series resistance [78].

B. Hot Electron and Irradiation Degradation in MOS Transistors and $1/f$ Noise

In this special issue Fleetwood, Meisenheimer, and Scofield give the state of the art in irradiation degradation and $1/f$ noise in terms of number fluctuations [13]. Vandamme, Li and Rigaud discussed on the Δn or $\Delta\mu$ origin of $1/f$ noise in MOST devices through degradation due to γ -irradiation or bias stressing [13]. A strong relation exists between $1/f$ noise before irradiation and the irradiation hardness measured as a shift in threshold voltage after irradiation. The $1/f$ noise, however, does not necessarily increase by degradation by γ -irradiation [79] or bias stressing [80], although an increase in surface state densities is often observed after bias stressing [80].

Bias stressing under hot electron conditions creates traps at the interface and in the oxide. The less dangling bonds in a nonstressed device the less traps will be created by hot electrons and the longer the lifetime of the oxide and the device will be. The possible double origin, ΔN and $\Delta\mu$, of $1/f$ noise in MOS transistors can explain the controversial results of the development of $1/f$ noise through degradation. A normalized way to discuss the progress of $1/f$ noise, in terms of either an α parameter or a relative noise S_1/I^2 , is better than absolute values to compare before and after degradation. This is because mobility, mobility degradation coefficient, the series resistance and the threshold voltage shift because of degradation as can be seen from the contribution of Vandamme, Li, and Rigaud in this issue [13].

VII. CONCLUSION

All types of noise, thermal, shot, RTS, generation-recombination, $1/f$, and $1/f^2$ noise play a role in reliability analysis. These components have to be separated by spectral analysis first.

The $1/f^2$ noise analysis at very large current densities is very successful at characterizing the lifetime of metallizations.

The generation-recombination noise analysis is very useful for quality estimation of III-V and II-VI compound semiconductors.

RTS noise in diodes and bipolar transistor, analog amplifiers or MOS transistors is a typical poor-quality indicator, and for submicron devices often unavoidable.

The thermal noise of a metallization under strong bias gives information on heat-contact quality or delamination problems of metal-based films.

The shot noise is a typical instrument to study photo and avalanche photodiodes.

Although we do not know much of the origin and nature of $1/f$ noise, it can be used as a complementary diagnostic tool for quality assessment of a semiconductor material or device. This is mainly based on the fact that:

- 1) Crystal defects created by ions or protons increase the $1/f$ noise.
- 2) Current constrictions and interfaces increase the $1/f$ noise.
- 3) An increasing number of crystal defects goes hand in hand with a decrease in minority carrier lifetime. Both result in an increase in $1/f$ noise for diodes and bipolar transistors.
- 4) Noise measurements are more sensitive to local current crowding and interface problems than resistance measurements only. This makes $1/f$ noise analysis very attractive diagnostic tool for modern submicron devices like MES, MODFET's, and MOST's suffering from series resistance problems.

A low α -value can point to: 1) a low mobility value due to impurity scattering, and 2) a high crystal quality. The latter is not necessarily true. Low values of α_{latt} , however, point to a high crystal quality. Lower α -values in areas with higher μ are a strong indication that the crystal quality is better there. This has been observed in bulk channel p-MOS transistors.

Some problems still remain: 1) γ -irradiation does not seem to increase the $1/f$ noise in homogeneous structures, but gives a large threshold voltage shift in MOST's. Therefore, $1/f$ noise should be measured at fixed effective gate voltage before and after γ -irradiation and expressed in α -values, in order to find a fair comparison between the devices before and after degradation, 2) sometimes opposite trends in the $1/f$ noise development by hot electron degradation make $1/f$ noise unsuitable as a diagnostic tool for MOST's.

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