Electrical noise as a reliability indicator in electronic devices and components

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Abstract: Low-frequency electrical noise is well accepted as a very sensitive measure of the quality and reliability of electrical components and electronic devices. It shows changes in magnitude very much greater than in the static electrical properties. The excess noise is due to defects and non-ideality in the device. Although the excess noise is a general indicator of quality there can be many physical processes that could be involved. These noise contributions are additive and therefore not easy to distinguish so that the noise is not so valuable as a diagnostic tool. Also, there is not a detailed understanding of some noise sources, such as in some semiconductor devices. Recently devices have continued to become smaller in size so that the noise signal has become more significant compared to the real signal and the number of individual defects involved has become fewer. This has resulted in a growing trend to the study of the time varying signal rather than the noise spectral density. A review is given of the developments in the subject over the last few years.

1 Introduction

It is now well established that electrical noise is a sensitive indicator of quality and reliability in electrical devices. This is directly parallel with mechanical systems. The production of extra noise within a device will naturally reduce its quality with respect of its use in a low noise system but the proposition is wider than this since such noise indicates non-ideal processes occurring which can degrade the operation of the device. The direct connection of high levels of noise with reliability, or the useful lifetime of the device, is less strong. Experiments on many systems have shown that the noise level rises as a device degrades during its life, or under stress, and also that a device which, immediately after manufacture, shows high levels of noise has a short life and noise is thus a sensitive and non-destructive reliability indicator.

The essential features of the use of noise are that it is a nearly equilibrium measurement, so that no stress is given to the device, and that it is much more sensitive than DC or AC measurements. These latter are averaged quantities and the change in their values is usually found to be much smaller than that of the noise. Thus, during stress the DC and AC values may change by 1%, while the noise may increase by an order of magnitude.

The aim of this review is to describe recent work and trends in this area, rather than go over the fundamental principles, which have been described earlier [1]. Thus the detailed understanding of the noise processes which occur will not be described here. All semiconductor devices are covered as well as integrated circuits and their constituent parts and discrete passive components such as capacitors and resistors. There is a full discussion of the thin film metal line interconnects of integrated circuits in the context of the important failure mechanism of electromigration.

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1.1 Uses

Since noise is very sensitive to the detailed operation of a device it is a very attractive quantity for a variety of diagnostic purposes. It can be measured under equilibrium conditions or during or after high stress. However the measurement techniques require special equipment, an electrically quiet environment and particularly very careful experimental work. Thus it is not well suited to industrial manufacturing conditions. The interesting experimental frequency range is between 0.1 and 100 000 Hz with the low-frequency end being much more sensitive since the noise is largest there. Since measurement periods are needed of many times the longest period in the spectrum, the experiments are inherently slow and cannot be used during the routine production of ordinary devices.

1.2 Quality

It is obvious to use the noise level as a criterion in the development and improvement of the quality of devices. This is not only for devices for use in low-noise applications but also more generally since the noise is found to be a good development parameter in general. Noise measurement techniques are more suitable for the development laboratory than the production environment. Especially at the research or early development stage, the noise can be a sensitive and non-invasive way to determine the mode of operation of the device and particularly to determine the reason for any non-ideal features of the characteristics. Sometimes noise spectroscopy may be the only way of determining this [2].

The noise level can be used as a sensitive production monitor even though the measurement is not very fast. The evaluation of the noise level of a drop-in monitor, one per wafer, can be a sensitive process monitor and relatively fast since it is for one sample and the time taken for the evaluation needs to be compared with the process time.

1.3 Reliability

Since it is found that the noise level increases at a much faster rate than the DC parameters as a device degrades under stress, or during its life, it can be used as a sensitive predictor of lifetime after a relatively short time. Thus a stress test to failure can be made with a simultaneous measurement of the noise. The initial rate of increase of the noise level can be related to the lifetime and this knowledge used over a short period of stress on fresh devices to predict their lifetime. Since only a short measurement time is needed for such a sensitive indicator this is almost non-destructive. If this analysis is performed at elevated stress and there is a knowledge of the lifetime under normal conditions, then this initial measurement may give an estimate of the life in service.

With less certainty, the equilibrium noise measurement may be used as a simple reliability indicator for fresh devices. For some high-reliability applications screening of all components is needed to remove any with possible poor performance. Noise is a good reliability indicator for such screening. The noise is measured for all devices after burn-in and the lowest noise devices selected for use. Since the noise from all sources add together, this method does not give information about the particular reliability problem, but it does have the advantage that it can detect many different sources of defect.

Note that noise is a very sensitive, but general, measurement so that a calibration of its behaviour must be made on each type of device which has a distinct design or manufacturing process and extrapolation about the behaviour may not be made between different fabrication regimes.

2 Basic principles

Electrical noise is the random fluctuation of the electrical quantity about its mean, or time-averaged value. For clarity it is perhaps easier to consider a specific quantity such as a current. This could be made up of several contributions which are added. Each of these contributions will fluctuate due to some microscopic process, thermal agitation or due to the quantised structure of the matter. The average value does not reflect the size of these fluctuations. Thus the noise gives information which is removed by the averaging process.

If the number of identical contributions decreases the average value decreases but the fluctuation decreases at a slower rate since the noise intensities add for uncorrelated events. Thus a larger relative effect is expected with smaller devices.

If the quality of the device decreases due to some stress perhaps an extra contribution to the total noise may arise with a larger level of fluctuation. The noise will increase more than the quantity itself. This perhaps requires a little more discussion since it forms the basis of the reason why the noise is found to be a good indicator of quality and also why this reflects on the reliability. If a device has been designed and constructed to perform a specific function then internal currents, for example, which do not contribute to the operation will be reduced as much as possible to increase its function and quality. Thus extra leakage currents or parasitic capacitances or resistances will be reduced as much as possible. The quality of the device can be measured by the small size of these non-ideal contributions. Stress or usage under elevated or even normal operating conditions may introduce such non-ideal components and reduce the performance and quality. Since these contributions reduce the functionality of the device they are undesirable, but not necessarily excessively noisy. Even if they contributed an average amount of noise they would decrease the signal-to-noise ratio of the device. In practice, however, it is nearly always found that these parasitic components and processes are excessively noisy. Thus we can say that non-ideal contributions to the device operation reduce the quality, can increase under stress and contribute excess noise.

The logical connection between the device quality and its reliability has had less study and is less certain. This is probably because the evaluation of reliability is a very lengthy process and is more remote from the design, development, construction and evaluation processes. The basic arguments are that during the lifetime, stressed or unstressed, the quality reduces gradually as the (noisy) non-ideal contributions build up and their size eventually leads to either a drift of the specifications outside the allowable range or catastrophic failure. This is not a definitive argument since the loss of performance, and hence quality, may be a slow process while the failure may be a separate rapid process of wear-out at the end of a normal lifetime. Alternatively, one could say that during the approach to failure some non-ideal contributions will get bigger. Thus we can say that there is likely to be a strong link between quality and reliability for many degradation processes.

The quantity usually measured for the noise is the spectral density, which is the frequency dependence of the time average of the intensity of that frequency component of the fluctuation about its mean value. Thus for a quantity Q with a time-varying part $q(f, t)$

$$S_Q(f) = \frac{1}{T}\int_T q(f, t)^2 \mathrm{d}t \qquad (1)$$

Because of the discrete nature of matter, the individual events contributing to the noise are step-like and develop a smooth variation only after summation over a large ensemble. The non-ideal contributions to the device operation are often large discrete events so that the averaging is less effective. The squaring and averaging removes all the phase information and the waveform of the time-varying signal so that the spectral density is far less revealing than the time-varying signal. This is now becoming very apparent since there is less statistical averaging as the number of defects or sources contributing to the noise is small in the very small devices now being made.

2.1 Types of noise

The noise contributions which are inherent to the operation of a device are the thermal noise and shot noise. The thermal, kT, Johnson or Nyquist noise is due to the equilibrium thermal agitation of the device and is revealed in its dissipative components. The shot noise is caused by the discrete nature of any process, such as the flow of units of charge. It only reaches its quoted maximum value if the individual events are uncorrelated. Thus shot noise may be reduced by increasing the correlation but thermal noise is controlled only by the loss in the device, at a given temperature.

The excess noise contributions, excess to the thermal and shot noises, are the components which are used as a measure of the quality and reliability. They are fluctuations in the resistance or emission within a device. They are apparent in the non-ideal components in the operation.

The basic contribution is the generation–recombination (g–r) noise which has a Lorentzian spectrum which is white below a characteristic frequency but drops as f^{-2} above this frequency. The basic process is the generation of a free carrier from a trap and its subsequent retrapping. The conductivity thus fluctuates while the charge distribution often remains the same. The spectrum is the uncorrelated ensemble average of many events with an average trapping–detrapping time giving the reciprocal of the characteristic frequency. A single event with random times in the free and trapped states, but with the same average periodicity as this random process gives the same spectrum but a very different time variation. Such a randomly alternating two-state pattern is called a random telegraph signal (RTS), or if it unusually large, burst noise. As devices decrease in size, observations are often of the individual suddenly varying events, rather than the smooth variations of conventional g–r noise.

If the individual events giving rise to the g–r signals have different characteristic times then the transition region between the white and f^{-2} regions of the spectrum is spread out over a frequency range and the frequency dependence is between these extremes. Many such spectra are observed and the detailed form depends on the relative weighting of the individual processes with different characteristic frequencies. This relation between the distribution density of the processes with frequency is related to the spectrum by the Dutta–Dimon–Horne equation [3]. The term '$1/f$ noise' is used for all noises with a power law variation for the frequency with exponents near unity.

In many systems the frequency is exponentially dependent on another variable, such as the energy in an activated process, or distance in a quantum mechanical tunnelling process. In these cases a uniform distribution of this exponent variable within the device naturally gives rise to a $1/f$ spectrum. This $1/f$ noise is very frequently observed in many systems and has been called by many names such as flicker noise, excess noise or current noise. One of the significant features of this noise is that it contains contributions from processes over a wide range of frequencies and appears to have the same properties at any time scale; it is scale invariant [4].

In nearly all electrical systems a model has been proposed and verified for the microscopic processes involved in the fluctuations of the $1/f$ noise [1]. The exception is in uniform semiconductors where fundamental mobility fluctuation of the carriers by phonons is proposed, but not fully verified. This is not of direct relevance here since it predicts a firm value for the $1/f$ noise and does not allow for the excess, non-ideal contributions.

Largely for historical reasons, the Hooge expression is used to quantify the amount of $1/f$ noise:

$$\frac{S_V}{V^2} = \frac{S_I}{I^2} = \frac{S_R}{R^2} = \frac{\alpha}{Nf} \qquad (2)$$

The first two equalities are valid in general for an ohmic sample. The quantity α is a measure of the noise and N is the total number of carriers in the sample. Initially α was thought to be a universal constant, 2×10^{-3}, but is now used only as a measure of the noise. It is now an indirect acknowledgement that the noise varies inversely with the volume if the noise sources are uniformly distributed.

The excess noise forms described above can account for many different observed spectra. At frequencies well below or above the characteristic frequency the g–r noise will appear as excess white or $1/f^2$ noise. It is also worth remarking here that this discussion has been about equilibrium noise. Although it is accepted that the processes causing most forms of excess noise continue to take place even with no current flowing, a voltage noise only appears when the device is biased. Extra sources of excess noise may appear if the sample is driven into a non-equilibrium state with large current flowing so that there is local heating or other local non-equilibrium processes. This is perhaps a more direct method of investigating defective devices.

2.2 Excess noise in non-ideal parts of devices

The excess noise, which is the reliability indicator, often originates in the non-ideal components or the non-ideal currents of a device. These might be a parasitic resistance, a loss in a capacitor, a leakage current or a defect in the material. It is thus absolutely necessary to have a full understanding of the DC and AC characteristics of the device, including any non-ideal behaviour, before embarking on an analysis of the origin of the noise. It is certainly inadequate to analyse the noise by assuming that the device operates by a standard textbook process. Also, the whole device, as it is actually produced, needs to be considered not just the design sketch, since sometimes the practical design is different in significant detail as far as non-ideal behaviour is concerned. Thus a device may be a mesa or fully buried; the gate lead of a MESFET may be brought across the substrate surface to a bond pad and this may leak; sometimes there are guard rings; small process steps such as MOST threshold implants or implants at the boundaries of channels may be significant and the device may have an important interaction with its substrate which may thus not be taken as inert. Non-ideal components in real devices which have been found to contribute to the noise include the g–r current in a bipolar diode or transistor, the resistance between the channel and drain or source contact of an MOS transistor and the surface g–r states where a depletion region reaches a surface.

The degradation and consequent failure during the lifetime of the device can be due to various causes. External effects are corrosion and electrostatic overstress. Here we will concentrate on the wearout processes associated with high temperatures, which accelerate many atomic effects, and high voltages. These temperature and voltage stresses can be enhanced and used as accelerated stresses. Typical defects are produced by the generation of highly energetic or 'hot' carriers in the local high fields in small devices with the deposition of this energy in a small part of the device to generate a local defect with an electrical property, such as an energy level within the forbidden gap. Temperature stress can increase the mobility of host and impurity atoms and also vacancies and other lattice structural defects. Voids, breaks and other geometric inhomogeneities may be created. Another stress which can be well controlled is irradiation by charged or neutral particles. If their energy is high enough, and there is an interaction at a lattice atom, the energy may displace a lattice atom to cause a structural and electrical defect.

2.3 Time variation of a noise signal

One trend that has been very apparent over the last few years is the move towards a study of the time-varying noise signal rather than the spectrum. This has been driven by the study of smaller devices in which the noise is generated by many fewer defects so that the individual events can be seen. Also there is an increasing concern about non-ideal effects such as discharges and breakdowns which have a very characteristic signature and are not so regularly random. The shape and periodicity of the waveform is much more revealing about the process occurring than the spectrum which is averaged over the sampled period and then several of these spectra are averaged.

Changes in the measurement technology have helped this evolution. The first spectrum analysers were analogue. The next generation had digital sampling and the FFT calculation of the spectrum produced a great advance in convenience within the important audio frequency band. However the sampling resolution was limited so that the actual waveform was not of high quality. Now the digitisation can be good and there is adequate space for the storage of the waveform so that the FFT can be calculated, or not, as needed. Other signal processing is also easily possible. Whereas the input waveform used to be monitored to look out for any unusual behaviour, such as a burst noise signal, which might invalidate the calculation of a spectrum, the full waveform is now the signal which is usual stored.

2.4 Background

In an earlier detailed review [1] the author described the excess noise in devices and the physical source of the noise up to 1993. The present review is an update of that work with recent developments. Since then there have been other reviews with different emphasis. The review by Vandamme [5] concentrates on semiconductor noise mainly based on a mobility fluctuation model and has discussions on contacts, current crowding and parasitic resistances. Claeys and Simoen [6] concentrate on the use of noise as a diagnostic of defects in semiconductors in order to improve the quality. G–r and $1/f$ noise are discussed for various traps in the bulk and at the surface. This spectroscopic approach has also been discussed by the present author [2]. Jevtic [7] concentrates on the use of noise as a reliability indicator. The recent review by Cioffi and Neri [8] is almost totally concerned with the noise in metal interconnects as they degrade under electromigration, although there is a section on hot electron damage in MOSFETs. Here we will try to cover the whole field and try to include the little work that has been devoted directly to reliability.

While the presence of a large, or increasing, amount of excess noise can be taken as a general indicator of a lack of quality or reliability, it should be noted that there may be problems in making further deductions. One problem is that noises are additive and often have similar $1/f$ spectra so that it is difficult to distinguish noise contributions, and hence their origin. There is a lack of understanding of the origin of most types of excess noise to a level at which quantitative estimates may be made. A good general review of the physical origins of noise is given by Kogan [9]. This is particularly a problem in bulk semiconductors for which there is not a good model. Naturally this means that it is not possible to predict the levels of excess noise by modelling.

These problems are decreasing with the trend to smaller devices where an individual defect is active and can be seen as a clear time signal. Models are being developed for these cases and the bias and temperature dependence of the time dependent waveform can be very informative, sometimes with too much data.

Particularly valuable approaches are being introduced in which the noise data are being correlated with other quantities such as the DC and AC characteristics or specific defect quantities such as deep level transient spectroscopy (DLTS) and mutual conductance dispersion. Sometimes two noises can be correlated to give more than twice as much data and confidence in its validity [10, 11].

3 Results in specific devices

3.1 Bipolar and Schottky diodes and bipolar transistors

A dominant excess noise source was established in the non-ideal, generation rather than diffusion, current of bipolar transistors and diodes [12]. This current can arise within the depletion volume due to g–r centres at mid-gap or at the silicon–silicon oxide interface where the depletion region meets the surface. With better manufacturing techniques the bulk source is now small and most attention is placed on the surface states. These are also the source of the excess noise in surface channel MOS transistors. Thus the noise in bipolar and MOS devices is converging. The noise increases with larger leakage currents, introduced traps and by irradiation.

A relation between a macroscopic defect in the junction, leakage current and noise has been observed [13]. The increase of interface state density by hot carriers produced when the junction is strongly reverse biased has been reported [14, 15]. Power diodes must have low leakage and sharp breakdown characteristics at a high reverse voltage. With large area devices there can be non-uniform current density with current crowding. Burst and $1/f$ noise has been considered a good way of detecting poor devices [16–18]. Attempts have been made to understand the mechanisms to develop a diagnostic tool but with little success. This current crowding effect has been investigated in solar cells, which also have a large area [19, 20]. The general topic will be discussed later.

A two-level or random telegraph signal seen in the waveform can be due to the g–r process of a single centre for a very small device. However, in large devices it is usually described as burst noise and is due to some single centre changing its charge to control the conductance of a high density current channel such as a dislocation pipe. Such dislocations and the resulting burst noise are now rare with modern processing technology. RTS noise due to oxide traps has been identified [21–23].

Investigations between the noise, characteristics and process details have been made on heterostructure [24–26] and avalanche photodiodes [27, 28].

More direct investigation between the noise and the quality has been given for Gunn diodes for screening purposes [29]. The degradation of the characteristics and increase in the noise has been recorded for Zener diodes [30]. There is good correlation and identification of the important parameters. A methodology of the use of noise as a reliability indicator for power bipolar transistors has been developed [31].

Polysilicon emitter bipolar transistors have extra excess noise sources due to the presence of silicon oxide between the polysilicon grains and at the single crystal–polycrystal boundary. There are surface states here, as at the interface at the surface of bipolar and MOS devices [32–34] and a more general review of degradation mechanisms has been given [35].

SiGe heterojunction devices show an increase in noise after hot carrier stress due to a reverse bias on the base–emitter junction [36, 37] as has also been seen in regular silicon devices.

Compound semiconductor heterojunction bipolar transistors (HBTs) have more defects because of the more complex crystal structure and difficult fabrication requirements. Considerable effort has been made to investigate the noise. The noise and surface recombination currents have been studied during burn-in with varying results [38, 39]. The use of the initial noise level as a reliability predictor has been verified for several devices subjected to stress although other variables can also be used [40–42].

3.2 MOS transistors

3.2.1 General: The overall aspects of the reliability of MOS devices and the degradation mechanisms can be related to specific causes and technological improvements can be proposed [43–45]. Noise is found to be a sensitive reliability indicator.

3.2.2 Radiation effects: While studies of commercial quality devices and the change in their properties with electrical stress is of value, the effect of radiation damage on the devices can give considerable information and is now quite well understood. Charge pumping and similar techniques to measure the various surface state densities are well developed, as is the description of the location of traps at, and near, the interface [46]. This allows detailed study of the noise and its origin [47–50].

3.2.3 Individual traps, random telegraph signals: The g–r noise, and the $1/f$ noise in the number fluctuation models, is usually thought to be due to traps at, or near, the semiconductor–insulator interface. These have a spread of relaxation times and are incoherent so the spectrum and waveform both become smooth. As devices become smaller, the individual traps involved can be distinguished as RTS noise.

Considerable information can be obtained about the behaviour of the trap, its activation energy and its cross-section from the temperature dependence of the on and off periods of its RTS signal and the amplitude. However after considerable effort very large variety of traps is found so that the overall behaviour may be lost in the detail [51–57].

3.2.4 Hot carrier and electrical stress: The most common form of stress is that due to excess voltage on the device. This is important since it will take place to some extent during normal operation and can be predicted to become a worse problem as device sizes are decreased. The normal damage is by the generation of hot carriers in the high electric fields along the channel. These carriers collide and may be extracted sideways into the substrate, and more important into the gate oxide. The energy is high enough to create lattice damage in the gate oxide and to create traps or current paths. The change in the DC or AC characteristics is small but the noise can increase considerably [58–68].

3.2.5 Silicon-on-insulator: New device geometries to reduce capacitances and hence increase the circuit frequencies include various semiconductor-on-insulator (SOI) technologies. These also introduce another silicon-insulator interface which can include interface states and resulting noise [69–71].

3.3 CMOS oxide currents and breakdown

As the size of devices is scaled smaller the thickness of the gate oxide is reduced. Although the gate voltages are also reduced, the field across the gate oxide is high and its breakdown is a major reliability concern. The breakdown can be hard or soft as the field is increased. A stress increases the defect density within the oxide and leads to a trap assisted tunnelling current in parallel with the normal tunnelling current. The passage of carriers through individual traps produces a large noise in this excess current. The noise can be used as a sensitive indicator of pre-breakdown [63, 72–77].

3.4 Series resistance effects

A common observation is that a large excess noise can occur in the non-ideal, or parasitic, components of a device. This is true for field effect transistors where the construction can result in a resistive section between the channel and the source or drain contact, especially under some bias conditions [78, 79].

3.5 GaAs MESFETs and HEMTs

Field effect transistors made from compound semiconductors suffer from a variety of electrical traps located at defects in the material, its surface or substrate. These defects can be due to the structure or chemical impurities. The materials and their passivating oxides are not as tolerant as silicon. The extra processing with different materials and lattice strain make heterostructure devices even more prone to defects. Such defects contribute severely to the quality of the device as seen by its performance, and defects with similar properties are produced by DC and RF voltage, temperature and radiation stress.

The complexity of these devices with many processing steps, substrate, capping and surface treatment layers and mesa and deep implantation stages gives considerable scope for noisy parasitic components. Although a room temperature characterisation may be adequate to determine the quality and to judge whether a process can be improved, a very full analysis using several techniques over a wide temperature range is needed. Thus DC characterisation with noise and one or more trap diagnostic methods such as DLTS, mutual conductance dispersion under several bias conditions is needed to determine the activation energy and cross-section parameters of the trap and its location in the device. Most frequently the traps are found in the substrate or surface [80]. DC and RF stress has been seen to produce traps in GaAs FETs [81–83]. General studies have been made on HEMTs [84, 85].

3.6 LEDs and lasers

The degradation of optical sources such as LEDs and lasers is important in communication systems. The stress can be voltage, temperature and light intensity, and the electrical or optical aspects of the device operation may be more susceptible to damage. There is an extra complexity in that there could be several parameters which could be used for measures of performance and voltage or current noise presented as data. A review has been given [86]. The effect of electrical stress on lasers [87–89] and LEDs [90, 91] has shown that the excess noise is a good reliability indicator.

3.7 Resistors

3.7.1 Non-uniform material and contacts: If the excess noise sources are distributed uniformly throughout the volume of a homogeneous conductor, as implied by eqn. 2, and they produce a resistance fluctuation, then the observed voltage noise across a sample is larger if the current flow is not uniform but is more heavily weighted towards the parts where there is a current concentration. This has been verified by experiment [92]. This immediately provides a very general reason why conductors can become noisy as they degrade and why parasitic resistances and contacts can be important excess noise sources as well as weak points for failure. The quality of an inhomogeneous conductor has been investigated [93]. Many different contacts have shown excess noise [93, 94–98]. The nonlinearity of a resistor, usually measured as the third harmonic signal, has been used as a convenient measure of the quality. This change in the resistance with current also produces a component of excess noise which can be called non-equilibrium noise. It can be measured as the noise appearing in the side-bands of the harmonics of the voltage developed when an alternating current is applied or in the spectrum of the rectified voltage developed when a series of current pulses of alternate sign, but the same height, are applied [99, 100].

3.8 Thick film resistors

Thick film resistors are often used in discrete or hybrid circuits. They are one of the earliest sources of $1/f$ noise in the form of granular carbon resistors. They are highly inhomogeneous so that the enhancement of the noise mentioned above is acute. They are assemblies of conducting grains in an insulating matrix. The conduction and noise can occur in the material within each grain, in the resistance of the, often non-ohmic, contact between grains and in the contact between the resistor and the external circuit. It is apparent that the resistive mixture should be as uniform as possible and also with a fine grain size. Experiments are notoriously difficult with such a poorly characterised material so that it is not always easy to distinguish the source of noise in the volume and another due to the external contacts. Noise is an obvious measure of the quality and has been used as a reliability indicator [101–108]. Another source of the noise is at the edges if the resistor is trimmed to adjust the resistance.

3.9 Thin film resistors

Thin film resistors are much better characterised since they are made of a more homogeneous metal alloy. However, higher specifications are normally expected. The noise sources within a well prepared metal film are small but physical defects and the contacts can be important. A review of the nature of the defects and the $1/f$ noise has been given by Zhigal'skii [109]. The noise and the non-ohmicity given by the third harmonic index are good measures of the quality and reliability, which is normally defined by the resistance drift. The distribution of the resistance within a batch after manufacture, as well as of these other quantities may be used as a process control parameter [110–114].

3.10 Percolation effects

If the contact resistance between the grains of an inhomogeneous system is increased then the number of possible competing parallel paths between the external contacts decreases and eventually the connectivity suddenly ceases. This is the interesting percolation problem and in an ideal model system this threshold occurs at a critical point corresponding to a critical value of some parameter such as the fraction filled with conductor or the fraction of conducting bonds on a random lattice. This is well reviewed by Kogan [9]. Model systems of various types have been investigated to illustrate the variation of the resistance and the noise on the approach to the percolation threshold [115–119].

3.11 Electromigration

With the decrease in size of all the components in an integrated circuit there is a stronger possibility of the failure mode of electromigration and the related stress migration in the metal interconnects between the active devices. As the metal line cross-section is reduced the current density increases and there is an increase in the momentum exchange in the resistance process between the charge carriers and the vibrating lattice atoms. This current-assisted diffusion produces an atomic flow. This flow is largely along grain boundaries and can be considered a flow of vacancies in the reverse direction. If there is a net convergence, or divergence, of vacancy flow a void may form and grow to produce an open circuit. In stress migration the driving force is not a current but the strain gradient produced by differential contraction between the metal and its surroundings.

The degradation process goes through stages with the motion of impurity and host atoms (vacancies) to form voids which grow, change shape and perhaps move until big voids form to create an open circuit. With such dynamic changes in the local resistivity and connectivity of the metal there will be resistance changes and hence excess noise. This noise is found to be a sensitive reliability indicator and shows increases by orders of magnitude while the resistance only increases by percents [8].

Considerable information can be obtained from the noise [120–130]. It is established that in the equilibrium film the noise has a $1/f$ spectrum and gives a measure of the diffusion activation energy of the mobile species [131]. During this stage the waveform is smooth and the noise well behaved as if from the summation of many sources. At high current densities, and after large voids have formed, the waveform becomes very discontinuous with large sudden transitions [132–135]. These events are very characteristic, but vary between samples. They correspond to void motion, formation and healing and can be studied by the addition of second harmonic measurements [136–138]. The spectrum of this waveform tends to $1/f^2$. This is an example of the value of studying the waveform as well as the spectral density [139].

3.12 Integrated circuits

The noise in various electronic devices has been studied to determine its value as a reliability indicator. The drift of the quiescent currents in integrated circuits shows good correlation with the initial noise [140–143]. The noise in the supply current has been found to be a good reliability indicator [144–146]. In MEMs circuits used in hostile environments the degradation by corrosion of the silicon or polysilicon can be important [147, 148].

3.13 Vacuum emission

Vacuum and field emission devices are becoming more common. The early sources of the flicker, $1/f$, noise were hot cathodes. In these devices the noise is caused by changes in the emission as low work function atoms migrate over the surface of the emitter [149].

3.14 Capacitors

Breakdown and pre-breakdown events in capacitors can be detected as current noise. This has been studied in solid [150–153], plastic foil [154–156] and electrolytic capacitors [157, 158] and most of these have correlated the initial noise with reliability or drift of the capacitance. For the electrolytic samples this mirrors the observations in pitting corrosion of sudden events in the electrochemical potential.

4 Conclusions

In most electronic systems there is clear evidence that excess noise is a sensitive reliability indicator. Its use as an industrial screening tool may not yet be technically sufficiently easy but as a research and process tool it is showing considerable value.

For many systems, especially those involved with pre-breakdown and the very small systems, the spectral density is now appearing to be a rather coarse indicator and there is a trend to the study of the more informative time-varying signal.

The role of defects, and the resulting large fluctuations is going to be more important as devices become smaller and may be the limit to the size of the present types of devices [159].

The most valuable results are those where the noise measurements have been supplemented by one or more other measurements in order to reveal the actual processes taking part and their location within the device.

There is a need for more development of measurement systems [99, 100, 160–162]. The correlation between various measured parameters is valuable and needs to be developed [11, 163–168]. Since the detail in the time waveform is lost when the spectral density is calculated more effort is needed for simple analysis of the waveform. The wavelet transform can be used to study elements of the structure of the wave [169]. In particular, methods to measure sudden events in a waveform, for example to automatically detect and measure RTS events, needs to be developed for offline and online use [170].

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Noise Spectroscopy of Semiconductor Materials and Devices

Josef Šikula and Ladislav Štourač

Abstract - The noise spectroscopy in time and frequency domain is used to give information on single carrier trapping and charge carrier transport in MOSFETs, Quantum dots, conducting film resistors, capacitors and single crystals. Defects in the vicinity of the p-n junction and MOS channel create the 1/f noise, the burst or RTS noise. The sources of fluctuation are quantum transitions of carriers between localised states and energy bands, carrier number and mobility. Noise reliability indicators are used to assess the device quality and reliability.

I. Introduction

The noise spectroscopy in time and frequency domain is one of the promising methods to provide a non-destructive characterisation of semiconductor materials and devices. This applies to both active and passive components, i.e., bipolar, quantum dots and MOS structures, on one hand, and resistors and capacitors on the other. As a main diagnostic tool it is proposed to use low frequency current or voltage noise spectral density and theirs statistical distributions.

It is known that most of failures result from the latent defects created during the manufacture processes or during the operating life of the devices. The sensitivity of excess electrical noise to this kind of defects is the main reason of investigation and use of noise as a diagnostic and prediction tool in reliability physics for the semiconductor devices lifetime assessment. The noise spectral density depends on stress and damage and varies among nominally identical devices. This component is called excess noise spectral density and therefore it is not of fundamental origin.

The sensitivity of the noise characteristics to the structure defects and other irregularities is typical feature of these methods. It is due to microphysical origin of fluctuation cased by quantum transitions of charge carriers. Noise depends on: i) perfection of the crystal structure, number of grain boundaries, point defects, linear defects, ii) surface parameters and iii) homogeneity and manufacturing quality of the device active region.

A possibility of the use of noise measurements in analysis, diagnostics and prediction of reliability of electronic devices was studied by many researchers [1 to 11]. It is supposed that defects are the actual sources of the excess current and the excess noise.

The actual reliability of electronic devices is usually less then the maximum theoretical value of reliability depending on the attained manufacture level. It may be due to irregularities in the manufacturing processes. It was observed that chemical condition of the surface could affect the magnitude of the noise spectral density.

In the present paper the application of noise spectroscopy on MOSFETs, quantum dots, thin and thick conducting film resistors, tantalum capacitors and CdTe single crystals is given.

Because due to stress and ageing the noise variations are much larger than those of the DC current components, our experimental studies are used for a quality and reliability characterisation.

II. Quantitative Characterisation of the Excess Noise

The fundamental 1/f noise spectral density is usually carried out by means of a generalised Hooge's formula

$$S_I = \alpha . I^2 / f . N \quad (1)$$

where S_I is the current noise spectral density, f is frequency, N is the total number of carriers in the sample active region, I is the device current and α is an empirical constant, which is now extensively used to characterise the device structure perfectness.

Theoretical values are typically of the order of 10^{-9} to 10^{-8} [10]. On the other hand, the values of α measured on

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the devices ranges from 10^{-3} (poorest samples) to 10^{-7} (currently the best samples).

It was proposed to define the quality and reliability indicator M_Q as

$$M_Q = S_I f/I^2 \qquad (2)$$

At present the concept of the excess noise as a quality and reliability indicator is generally used. There is also a variety of measuring set-ups and measuring conditions. Not all of them provide the best attainable resolution. Generally speaking, one has to be able to distinguish the excess noise of the device, which carries information on the device condition, from the background noise. To get a good measurement resolution, it is necessary to carry out the measurements in the region, where the expected noise component magnitude is distinctly higher than that of the background.

III. Burst and RTS Noise

The present models of the burst and RTS noise are based on three measurable quantities. In the time domain these are the burst amplitude and two transition intensities. In the frequency domain, the Lorentzian relaxation time, the low frequency value of the spectral density, and the maximum spectral density when the electron Imref coincides with the trap energy level. All models presented up to now can explain the bistability of the system, which is caused by the defects in the device structure. For the forward- biased p-n junction devices the burst noise sources are defects in the vicinity of the junction. The development of submicron technologies has lead to new type of burst noise called the RTS noise, the sources of which are carrier number and mobility fluctuations caused by random capture and emission of carriers on a trap located near the channel. During the last decade this phenomenon has been studied for the Si-SiO_2 interface using both n and p channel.

A. InGaAs Quantum Dot

Quantum dot (QD) structures have attracted much attention because of interest in not only the relevance of low-dimensional electron gas physics but also future applications of high-density, low power, and highly functional integrated circuits. Tacano et al. [14] fabricated an AlGaAs/InGaAs heterojunction field-effect transistor (FET) memory cell in a tetrahedral-shaped recess (TSR) structure, which has a hole-trapping QD as a floating gate, and succeeded in observing RTS noise in the retention characteristics of the memory cell. RTS observed in short- and narrow-channel FET are direct evidence of a single charge capture and emission. An analysis of RTS in this work quantitatively explains details of hole trapping processes in the TSR QD.

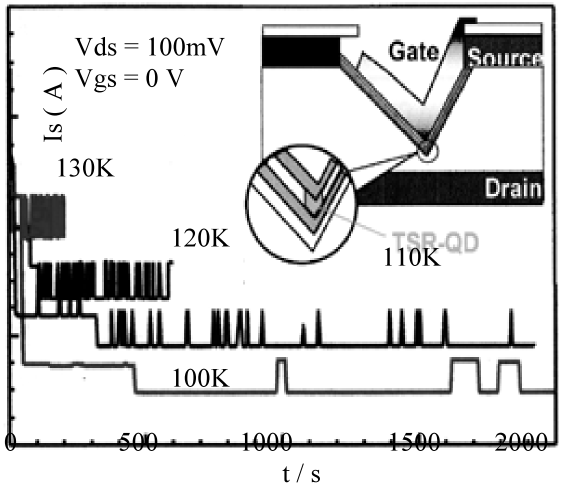

Fig. 1. RTS from QDs at various temperatures

Temperature dependent RTS pulses (Fig.1.) are excited up to 130 K, and the activation energy of a hole capture and emission processes were estimated as:

$$Et_1 = 190 \text{ meV and } Et_2 = 260 \text{ meV}.$$

Similar value of the activation energy was found in MOS structures (see Schultz et al. [15])

B. RTS in MOSFETs

It is supposed to be caused by individual traps, which can be either in silicon, or the oxide, or in the interface between the silicon and the oxide. Its position results on the time of the RTS pulses. For the trap located in the channel or in the boundary between the oxide and silicon at the gate side, the mean pulse time for an n-type semiconductor with a carrier concentration of 10^{16} cm^3, the capture cross section $10^{16} cm^2$ and a thermal velocity of 10^7 cm/s is 0.1 microseconds.

If the trap is located in the oxide then the capture τ_c and emission τ_e time constants will be longer because of tunnelling. The tunnelling time increases with the trap depth exponentially and for a depth of 1 nm the characteristic time is of the order of 1 second. The capture time τ_c is inversely proportional to the square of the drain current I_D as is shown in Fig. 2. Single carrier trapping and phenomena associated with it has been discovered in tunnel diodes, tunnelling microscopes, MESFETS, etc. The RTS noise is responsible for high noise levels and make also source of a 1/f spectrum, which is regarded as originating from the superposition of partial RTS spectra [15,16].

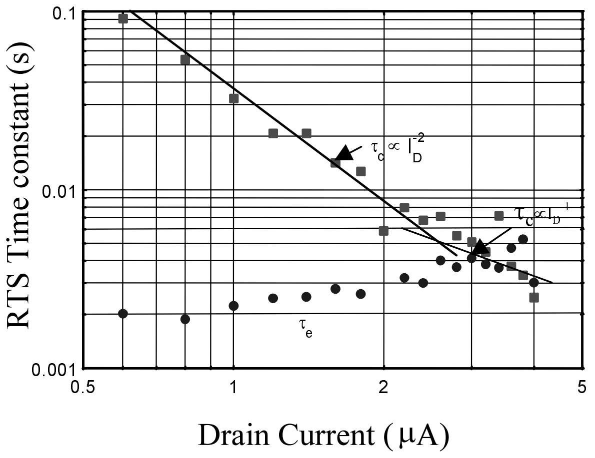

Fig. 2. Capture τ_c and emission τ_e time constants of a small-area Si n-MOSFET

C. Thick Conducting Films

The physical model for the electrical conductivity of thick film layers is based on the assumption, that charge transport is due to electrons thermally emitted from metallic grain and its transfer to second grain has a main component given by tunnelling. Electric field intensity has very low value inside grains and strong field exists between them. This case represents electric field assisted thermionic emission and electric field activated tunnelling.

There are two experimental ways to characterise fluctuations in a conducting film layer. The first is based on the realisation in time domain (see Fig. 3.) and in this case the voltage average value, probability density and distribution function can be obtained. Burst noise is an important indicator of a single trap activity in a small subsystem with a small number of free carriers. Defect region has small dimensions and is submitted to high electric field and high current density. Such defect often appears due to laser trimming.

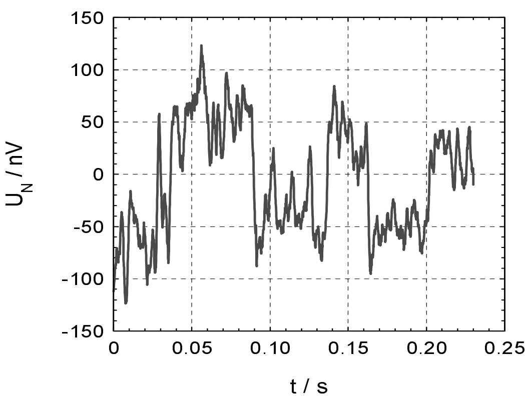

Fig.3. Burst noise voltage time dependence

Therefore it often degrades faster and at least shows a poor noise behaviour.

Noise spectral density frequency dependence of this type of noise is given in Fig.4. for a resistor R = 8 kΩ. It is superposition of 1/f noise and g-r noise, with Lorentzian shape cut-of frequency f_c = 20Hz. This frequency corresponds to average pulse time constant 50 ms.

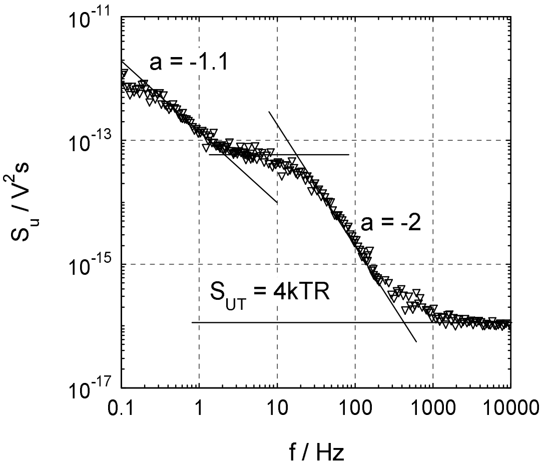

Fig.4. Noise spectral density frequency dependence

D. Metallic Thin Films

We have found burst noise in metallic thin film resistors of resistance higher than 100 kΩ made by different manufacturers. Such a type of noise is probably generated in cracks or structural defects, where current density is much higher than its average value. We suppose this region has dominant influence on device lifetime [9]. Stochastic process describing fluctuations in thick film resistor can be considered as a Markovian and then we suppose, that noise voltage is proportional to the current or voltage dc value (see Fig. 5).

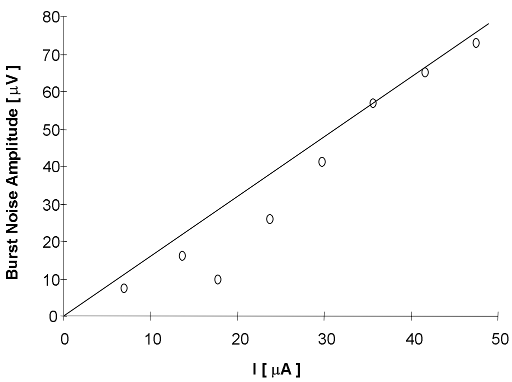

Fig.5. Burst noise amplitude vs. DC current

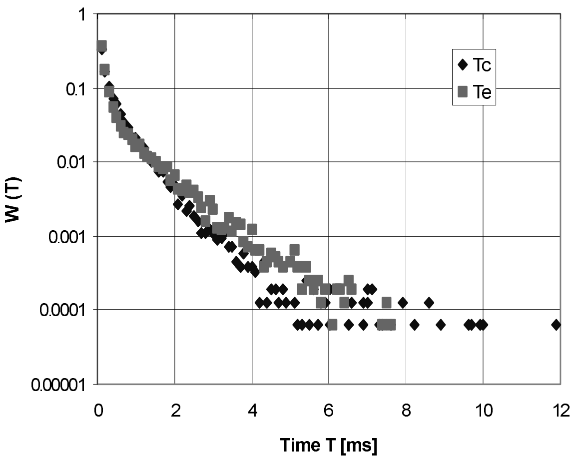

Fig. 6. Probability density distribution for T_e and T_c at biasing 13.7 V for resistor 1 MΩ

Probability density distribution of emission T_e time and capture T_c time is shown for thin metallic film resistor 1 MΩ in Fig. 6. It is given by superposition of two exponential distributions. Short times have higher probability due to 1/f noise component.

E. Tantalum Capacitors

Noise spectral density is a quadratic function of the current, when the electric field strength in isolating layer is so low that avalanche process cannot occur. Measurement performed at very low frequency range 10 mHz to 1 Hz reveals, that for some samples noise is $1/f^{a}$ type, but we observed some time instability, which is probably related to self-healing process [17,18]. This process occurs in defect spots of dielectric layer, where a Joule heat is generated due to excess current. The self-healing is based on the high temperature transformation:

$$MnO_2 + \text{heat} \rightarrow Mn_2O_3$$

The Mn_2O_3 form has several orders higher resistivity than MnO_2 and then the dielectric breakdown is interrupted and the sample quality improves.

We observed that after self-healing event, the noise spectral density decreases, but in some cases the burst noise is not removed (see Fig. 7.) We can conclude that due to self-healing – the $1/f^{a}$ noise is changed into the superposition of the burst noise and $1/f^{a}$ noise with lower noise spectral density.

The frequency dependence of noise spectral density in mHz region gives information on slow irreversible processes of tantalum pentoxide crystallisation and oxide reduction. The self-healing process can improve sample quality due to leakage current and noise reduction.

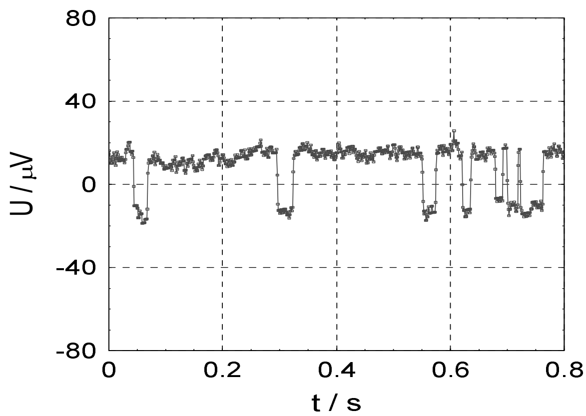

Fig.7. Time dependence of noise voltage after self-healing event

IV. Noise and Mobility of Carriers

To explain experimental dependencies of noise spectral density on voltage, length and width, we will introduce power noise spectral density S_P by

$$S_P = S_U/R = S_I R \tag{3}$$

This quantity corresponds to voltage or current fluctuation on sample with a resistance R. Type of a voltage, length and width dependencies are similar as for mono-crystalline material. From this point of view we suppose, that noise behaviour of homogeneous samples can be described by a Hooge's model.

In this case the power noise spectral density S_P is proportional to electric power dissipated by one current carrier P_0 and inversely proportional to frequency

$$S_P = \alpha P_0/f \tag{4}$$

where α is proportionality constant,

$$P_0 = e\mu E^2 \tag{5}$$

μ is charge carrier mobility, E is electric field intensity.

Total power noise spectral density including thermal noise is given by

$$S_P = 4kT + \alpha\mu e E^2/f \tag{6}$$

When burst noise source is active, then this component is add to 1/f noise spectral density as is shown in Fig. 8. At frequency 1 Hz burst noise spectral density is one order higher than the 1/f noise for applied voltage 10.5 V.

Cut-off frequency f_c for which 1/f noise spectral density has the same value as a thermal noise density

$$f_C = \frac{\alpha\mu .eE^2}{4kT} \tag{7}$$

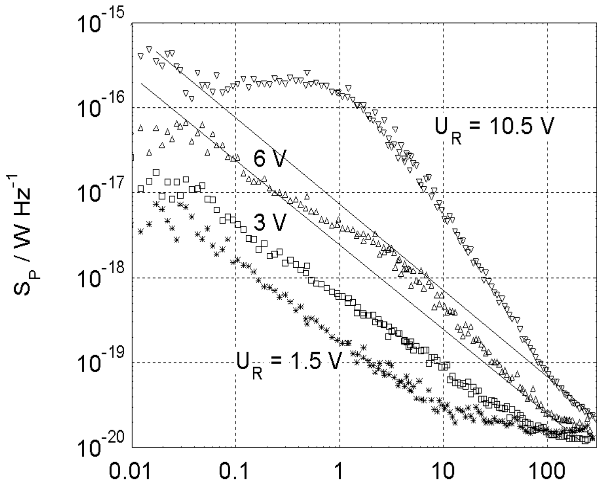

Fig.8. Power noise spectral density for thick film resistor 1 MΩ

From this point of view thick conducting films can have the same noise characteristics as thin conducting films, when the sample length is the same.

Quantity a_μ is given by

$$a_\mu = \alpha.\mu \qquad (8)$$

does not depend on sample length and width. This quantity has a unit of mobility and can be used as a measure of conducting material quality (see Table1).

TABLE1.
QUANTITY a_μ FOR DIFFERENT CONDUCTING FILM MATERIAL

Paste	A	B	C	D
a_μ/m^2/Vs	1.10^{-5}	8.10^{-5}	4.10^{-5}	2.10^{-5}

A. CdTe Crystals

The recombination mechanisms of light illuminated CdTe crystals can be described by the four-level g-r model. This approach arises from the assumption that the Hooge's formula (1) is applicable to one type of charge carriers only, i.e., separately for free holes and separately for free electrons. However, to examine the effective transport mobility, we must include holes and electrons simultaneously into the transport equation. This is the reason, why different effective noise and transport mobility occur. The plots of the light generated charge carrier density, effective transport mobility and effective noise mobility versus the light intensity of the illuminated CdTe crystal is shown in Fig.9.

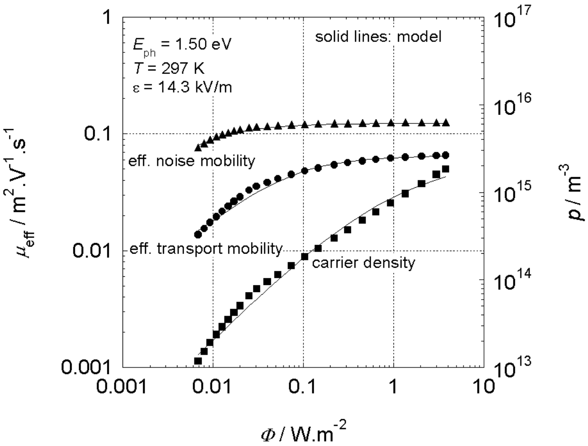

Fig. 9. Charge carrier density, transport mobility and effective noise mobility v.s. the light intensity.

Theoretical values of carrier density and mobilities (solid lines) are calculated from the four-level non-linear recombination model. The triangles, circlets, and squares have been calculated from experimental lux-ampere characteristic [19].

We may conclude that there are two effective carrier mobilities: one for the transport and the other for the noise characterization.

Under the previously mentioned conditions, the 1/f noise parameter, α, ranges from 4×10^{-4} to 2.5×10^{-3} for CdTe crystals, depending on the incident light intensity and electric field strength. It is interesting, that the parameter α is lower for higher electric field across the sample at the same photocurrent. In such a way, we can increase the signal to noise ratio of the CdTe detectors by applying higher electric field intensities.

The noise measurements allow us to assess the quality of our CdTe samples. As a quality indicator we may take the 1/f noise parameter α, which is not constant [8]. Lower α's indicate better-quality samples.

V. CONCLUSION

It was proposed as a quality and reliability indicator a normalised 1/f noise spectral density. Burst noise amplitude has its maximum value when the electron Imref coincides with the trap energy level. Then in quantum dots and MOS structures the burst noise appear in a short temperature range. All models presented up to now can explain the bistability of the system, which is caused by defects in the device structure.

Burst noise component shows that the thick conducting layers are composed of chainlike structure of metal grains separated by semi-conducting or insulating layers. In tantalum capacitors the self-healing process decreases the $1/f^{\alpha}$ noise.

Power noise spectral density of 1/f noise is proportional to power dissipated by one charge carrier and inversely proportional to frequency. We may conclude that there are two effective carrier mobilities: one for the transport and the other for the noise characterization.

ACKNOWLEDGEMENT

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Low frequency noise in organic solar cells

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Abstract—**The conduction mechanism in organic heterojunction solar cells (OHSCs) has been discussed based on the results of low frequency noise spectroscopy. We prepared OHSCs composed of poly-(2-methoxy-5-(3',7'-dimethyloctyloxy)-1,4-phenylenevinylene), regioregular poly(3-hexylthiophene) and [6,6]-phenyl-C_{61}-butyric acid methyl ester. The devices prepared exhibited 1/*f* noise at the bias voltage range from +2 V (forward) to -2 V (reverse). It was found that there were three regimes in the noise spectral density $S_i(f)$ in the forward bias voltage region. In the ohmic regime, $S_i(f)$ increased in proportional to the square of current. In the trap filling regime, $S_i(f)$ was constant, while it increased again in the space charge limited current regime. In addition to this behavior, the noise spectra of OHSCs in the reverse bias voltage region exhibited the superposition of 1/*f* noise and the generation-recombination noise indicating the existence of carrier trap sites. These phenomena observed were thought to result from the breakdown and/or alleviation of the conduction path, which was caused by thermal stress of current flow.**

Keywords-component; low frequency noise; organic solar cell; variable range hopping conduction; 1/f noise; power spectral density

I. Introduction

Molecular-based electronic devices such as light-emitting diodes, photovoltaic cells and field-effect transistors have shown impressive improvements in their performance in the last decade [1]. Particularly, polymer solar cells have attracted considerable attention because of their advantages in low cost, mechanical flexibility, lightweight, and simplicity of fabrication. The optical properties of polymers can be tuned by modification of chemical structures. The efforts have improved the conversion efficiency of polymer solar cells up to 5.15 % [2], which is, however, still lower than that of silicon-based solar cells. The understanding on the transport and degradation mechanism is required for further improvement.

The low frequency noise spectroscopy has been used as a powerful method to study the intrinsic dynamics of carriers and the degradation mechanism of inorganic semiconductors [3]. Recently, the noise measurement has been applied to organic materials to investigate the conduction mechanism [4,5]. These reports have shown that the low frequency noise largely depends on intrinsic transport mechanism. In the present study, we have discussed the conduction mechanism in OHSCs based on the results of low frequency noise spectroscopy.

II. Experimental

Figure 1(a) shows a schematic of the device structure used in the present study. Indium tin oxide (ITO) was patterned by etching with an acidum hydrochloricum and zinc. The ITO coated glass substrates were cleaned in an ultrasonic bath in aceton and iso-propanol, followed by ozone cleaning. Structures of organic materials are shown in Fig. 1(b). Poly-(2-methoxy-5-(3',7'-dimethyloctyloxy)-1,4-phenyleneviny-lene)) (MDMO-PPV), regioregular poly(3-hexylthiophene) (P3HT), [6,6]-phenyl-C_{61}-butyric acid methyl ester (PCBM), and poly(3,4-ethylenedioxylenethiophene)-poly(stylenesulfo-nic) (PEDOT:PSS, 1.3 wt%) were purchased from Aldrich and used without further purification. A layer of PEDOT:PSS was prepared on ITO by spincoating at the following sequence: 500 rpm, 5 sec; 4000 rpm, 120 sec; 5000 rpm, 120 sec, and by drying at 110 °C for 40 min in air to yield a dried film with a thickness of approximately 40 nm. Subsequently, a mixed solution of MDMO-PPV and PCBM (MDMO-PPV:PCBM=

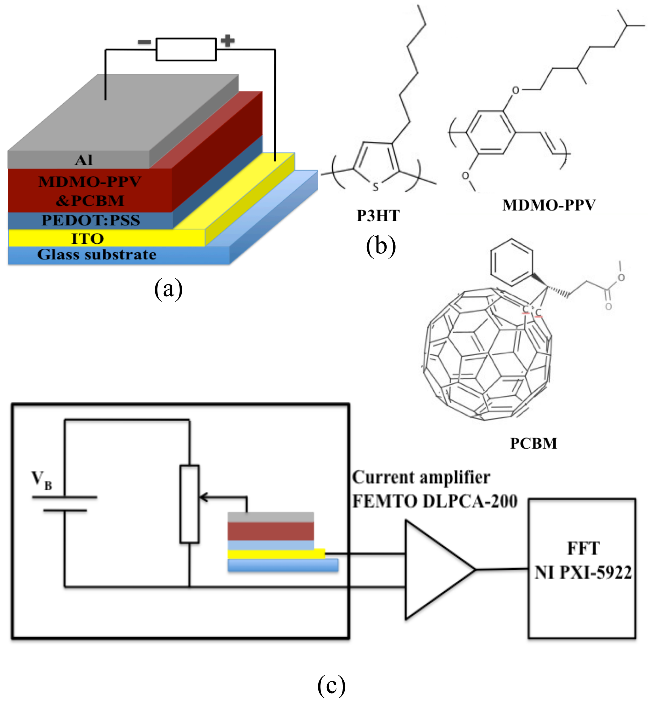

Figure 1. (a) Schematic of an organic solar cell. (b) Chemical structures of PCBM, MDMO-PPV, and P3HT. (c) Electric circuit for low frequency noise measurement.

1:4) in chlorobenzene was spun on the PEDOT:PSS layer at 4000 rpm for 40 sec, and baked at 70 °C for 40 min. In a similar manner, a spin coated film was also prepared from a mixed solution of P3HT and PCBM (P3HT:PCBM=1:0.8) in chlorobenzene. The specimen was then transferred into a vacuum chamber at the base pressure of 10^{-5} Pa, in which Al was evaporated through a shadow mask of 2×2 mm^2.

The noise measurement setup is shown in Fig. 1(c). Due to the high resistances of the devices, the noise in current was measured by applying a constant voltage to the devices. We used two probes configuration for noise measurements since high resistances of the samples made it difficult to use both five-probe ac and four-probe dc techniques. To prevent ac pickup and interference from other sources of electromagnetic fields, all units of the setup were electrically screened. The voltage supply was provided with lead batteries and divided using a potentiometer. Current fluctuations was amplified with a low-noise current amplifier (FEMTO, DLPCA-200) and subsequently processed with a fast fourier transform (FFT) analyzer (National Instrument, PXI-5922).

III. Results and Discussion

Generally, the noise spectral density of semiconductors is expressed by the following Hooge's empirical equation:

$$S_i(f) = \frac{AI^\beta}{f^\gamma}\ , \tag{1}$$

where $S_i(f)$ is the spectral density of current fluctuation, A is the noise magnitude coefficient, I is current, f is frequency, and the exponents β and γ are constant. Figure 2 shows the spectral density $S_i(f)$ for OHSC as a function of frequency. The measured noise was a $1/f^{\gamma}$ noise (γ~1) in the given frequency and bias voltage ranges (from -2 to 2 V). The triangles are the noise spectral density of the measurement setup. An OHSC was replaced by a 100 kΩ metal-film

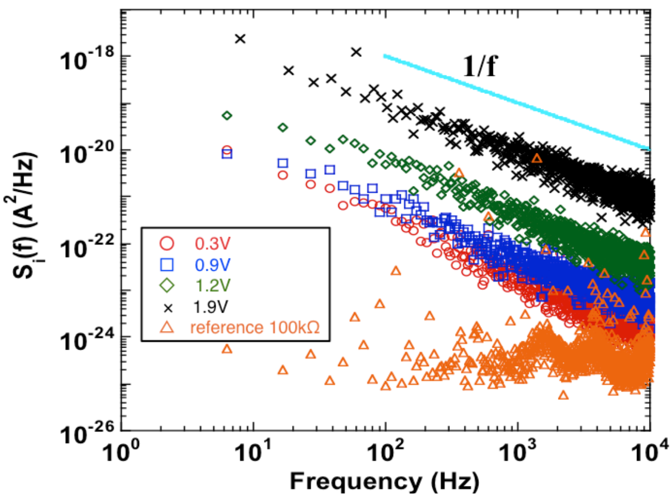

Figure 2. Typical spectral density of the current fluctuations for an organic heterojunction solar cell, measured at various forward bias voltages from 0.3 to 1.9 V. The slope of $1/f$ is shown as reference. The open triangles show the spectral density for a 100 kΩ metal film resistor.

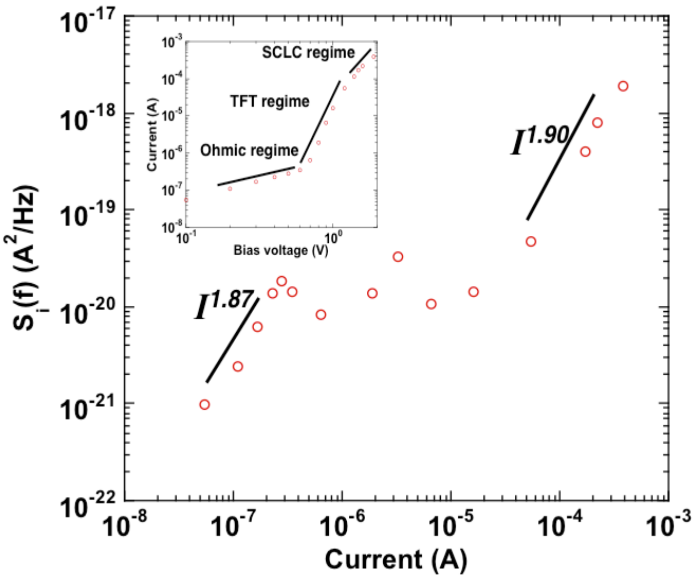

Figure 3. Plots of the noise spectral density $S_i(f)$ at f=10 Hz as the function of current. The inset shows the current-voltage characteristic of the device.

resistor (close to an organic solar cell's resistance). It was confirmed that the spectral density was derived from the organic solar cells.

Figure 3 shows the current dependence of the noise spectral density $S_i(f)$ at f=10 Hz. It was found that there were three regimes in $S_i(f)$ in the forward bias voltage region. This trend corresponds to that of the current-voltage characteristic of OHSCs (inset), that is, ohmic, trap filling transition (TFT), and space charge limited current (SCLC) regimes.

In the ohmic regime, the spectral density of current fluctuations varied as $S_i(f) \propto I^\beta$ (β~2). This behavior is also reported in the noise spectra of inorganic semiconductors [6]. From Eq. (1), the noise magnitude coefficient A was ~2.3×10^{-7}. Almost the same value was obtained in the spectral density in the reverse bias voltage region (A~2.5×10^{-7} 1/Hz). It was thus considered that the mechanism of current fluctuation in the ohmic regime was almost identical both in forward and in reverse bias regions.

The noise coefficient A is inversely proportional to the total number of carriers ($A \propto 1/N$) when the current fluctuation is the origin of mobility fluctuation [6]. In this case, N relates to the square of current as $N \propto I^2/I_0^2$. Accordingly,

$$A \propto \frac{1}{N} \propto \left(\frac{I}{I_0}\right)^{-2}, \tag{2}$$

where I_0 is the dark current.

Figure 4 indicates the dependence of the noise coefficient at 10 Hz on the ratio of photocurrent to dark one at the reverse bias voltage (-0.5 V). A halogen lamp was used as the light source. The noise coefficient A is inversely proportional to the square of the ratio of photocurrent to dark current. Therefore,

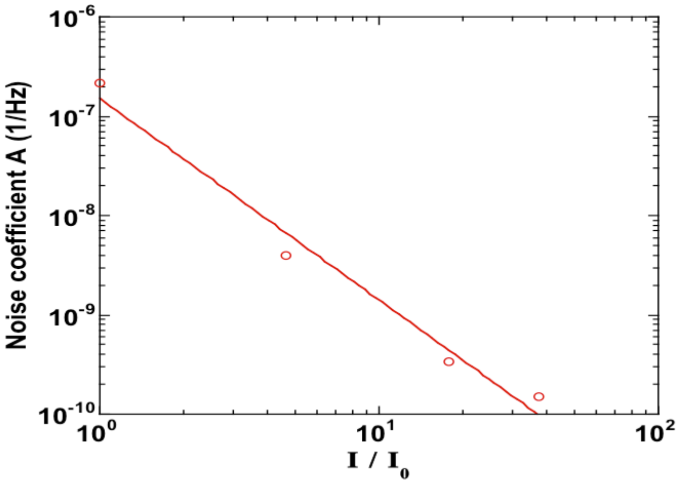

Figure 4. Plot of the noise coefficient A as a function of the ratio of photocurrent I to dark one I_0. The bias voltage was -0.5 V and the frequency was 10 Hz.

it was concluded that current fluctuations in the ohmic regime and reverse bias voltage region are derived from the mobility fluctuation. This mobility fluctuation originates from the conduction mechanism of variable range hopping in organic semiconductors [7] as well as the percolation effect in the mixture of MDMO-PPV and PCBM. In the reverse bias voltage, noise spectral density was the superposition of $1/f$ noise and generation-recombination (G-R) noise. The G-R noise observed were thought to originate from the breakdown and alleviation of conduction path, which was caused by thermal stress of current flow.

In the trap filling transition regime, the noise spectral density was constant. In this regime, total number of carriers is the sum of intrinsic carriers in the solar cell and injected ones from electrodes. The increase of number of injected carriers inhibited the increase in the noise spectral density.

In the SCLC regime, the spectral density of current fluctuations varied as $S_i(f) \propto I^{\beta}$ (β~2). The fluctuations of SCLC in inorganic diodes were studied in detail previously [8]. Authors revealed that the spectral density in the SCLC regime is expressed as:

$$S_i(f) = \frac{\alpha}{f} \frac{eL}{5S\varepsilon_0\varepsilon_r} V \ , \qquad (3)$$

where ε_0 and ε_r are, the relative dielectric constant of the material and the vacuum permittivity, respectively. S, e, and L are the area of sample, elementary charge, the thickness of sample, respectively. α is the SCLC Hooge parameter. We estimated the α value for the devices prepared, which was α~10. This value was larger by four orders of magnitude than that of inorganic SCLC diodes and this value was even 10 times larger than that of an organic diode [9]. These differences indicate the effect of the heterogeneous property in the organic heterojunction solar cells.

IV. Conclusion

We investigated the low frequency noise in organic solar cell. The measured noise was $1/f^{\gamma}$ noise (γ~1) at the given frequency and bias voltage ranges from -2 to 2 V. There were three regimes in the noise spectral density $S_i(f)$ in the forward bias voltage range, corresponding to the conduction mechanisms of ohmic, trap filling transition and SCLC. It was considered that the fluctuations in current in the ohmic regime were derived from those in carrier mobility. In trap filling transition regime, $S_i(f)$ was constant. An increase in the number of carriers injected into OHSCs inhibited the increase in $S_i(f)$. In the SCLC regime, the fluctuation in current was derived from the fluctuation in carrier mobility.

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NOISE CHARACTERISTIC OF SOLAR CELLS UNDER VARIOUS ILLUMINATION

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Abstract

Research of stationary, transport and noise characteristics of different type of PN junctions shows that illumination of PN junction can have influence not only on origin photocurrent and photovoltage, but also to noticeable changes of space charge regions quality. This phenomenon was observation so only on heterojunction based on $A^{II}B^{VI}$ compounds [1]-[2]. Simultaneously no one influence of illumination has been found on space-charge regions characteristics of a number of homo and heterojunction based on $A^{III}B^{V}$ compounds [3]. Behaviour of low-frequency signal noise in cooled InSb photodiodes show variety of features also in this case predicating occuring changes in space charge region [4]. Monitoring of noise characteristics makes possible to better analyse qualities and reliability of solar cells [5-7]. In this work was undertaken admeasurement of 1/f noise silicon solar cells of area about 104 cm^2.

Experiments were carried out on PN junction silicon solar cells prepared by boron diffusion in p-type Si wafers of area about 104 cm^2. These measurements were taken at room temperature T = 300 K. The source of illumination is a Halogen Lamp (55 W) connected to d.c. stabilized power source to obtain different level of illumination intensities (L) related to the lamp current shown in figure 2.

The dark and illuminated I-V characteristics for a typical Si solar cell n^+pp^{++} PESC of area about 104 cm^2 (for a chosen sample No. 20/2) in reverse direction are shown in figure 1. The illuminated curves were obtained with a halogen lamp (55W) In reverse direction as L the photocurrent increases until it reaches its saturation value (the short circuit I_{sc}). The changes of the numbers of electron-hole pairs produced current with increasing illumination intensity L indicates that the illumination increases the photocarriers passing the depletion region layer.

Experiment results and evaluation

Fig. 1 shows the current versus reverse voltage plot for No. 34V2 solar cell PN junction for various illumination levels and an ambient temperature of 300 K.

Fig. 2 shows the reverse current, as measured at U_R = 2V, to grow with the PN junction incident light intensity, for samples No. 34V2 a VS11.

Fig. 3 illustrates the noise voltage spectral density versus forward voltage plots, for sample 34V2, both in the dark and when lighted with L = 260 lx.

The noise voltage was picked up across a load resistance $R_L = 100\,\Omega$, at a pass band mean frequency of 1 kHz and a bandwidth of 20 Hz.

It is seen that the maximum value of S_{UM} is lower under illumination than in the dark and the maximum value position is shifted to higher forward voltage values. This is connected with the light-induced drop in the junction differential resistance.

It is evident from Fig. 4 that the samples are generating a G-R noise with a relaxation frequency of about 800 Hz when in the dark. At lower frequencies, 1/f noise is predominating.

If the sample is illuminated with light of intensity L = 260 lx, G-R noise is observed throughout the frequency band under 10^4 Hz. In this case, the relaxation frequency is below 1 Hz and, in regard of the Unipan 233 selective nanovoltmeter measuring range available, it could not be observed. Thermal noise of the experiment setup is predominant at frequencies above 10^4 Hz.

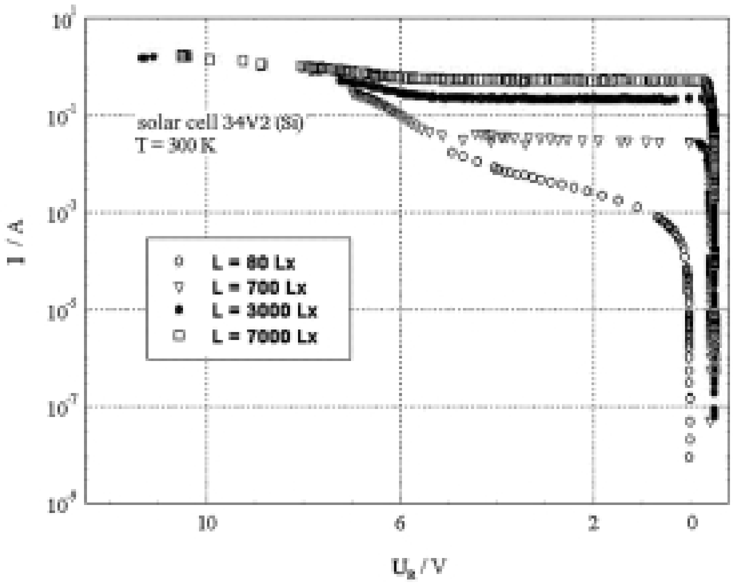

Fig. 1. *Dependence of current versus voltage solar cell No. 34V2 in various illumination levels and temperature 300 K.*

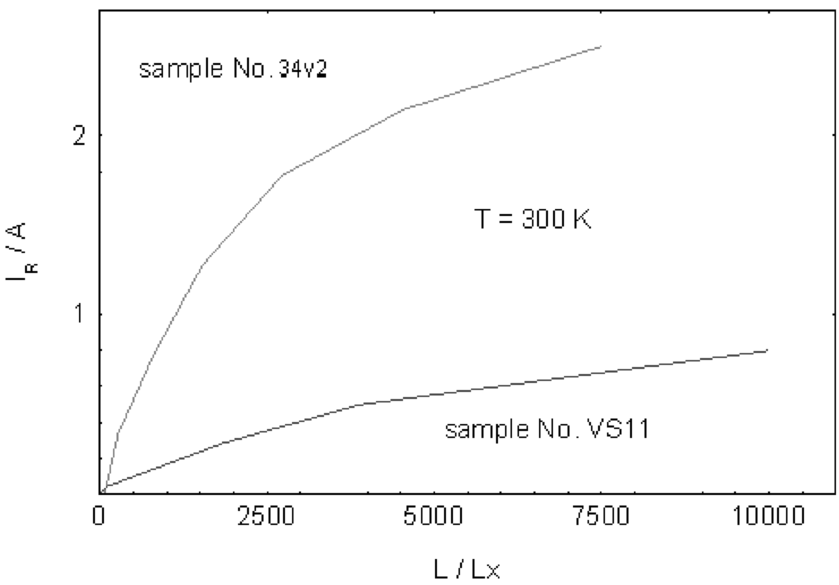

Fig. 2. *Dependence of reverse current versus illumination of solar cell No. 34V2 and VS11 and temperature 300 K.*

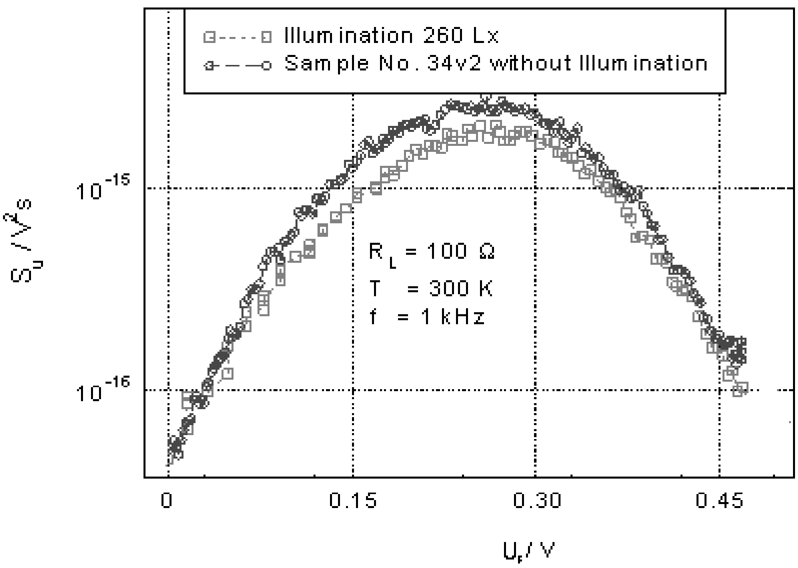

Fig. 3. *Dependens of noise voltage spectral density versus forward voltage of solar cell No 34V2 without illumination and with illumination 260 Lx.*

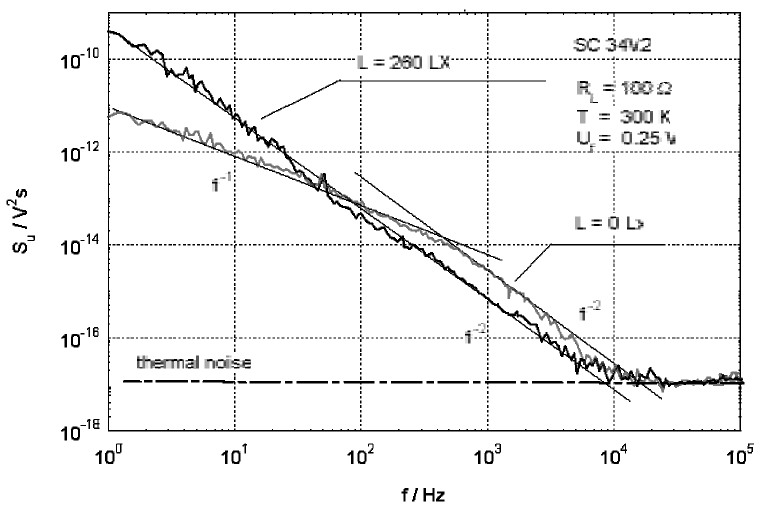

Fig. 4. *Dependense noise voltage versus frequence solar cell No. 34V2 for diferent illumination*

Conclusion

When illuminated, the samples under study appear to produce G-R noise whose relaxation frequency is below 1 Hz. The light-induced noise spectral density drop which was observed at frequencies around 10^3 Hz, with respect to the dark values, is due to the decrease in the PN junction differential resistance, which is caused by illumination. On the other hand, higher noise spectral densities, compared with the dark sample values, as measured at frequencies below 10^2 Hz, are due to the occurrence of 1/f noise in these samples in the dark.

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Noise as a tool for non-destructive testing of single-crystal silicon solar cells

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Abstract

Transport and noise characteristics of forward and reverse biased single-crystal silicon solar cells were measured in order to evaluate the solar cell technology. Stress comprising an temperature of 400 K and a DC electric field were applied to a total of 20 solar cells for a period of 5000 h. The samples were quality and reliability screened using noise reliability indicators. From the measurement results it follows that the noise spectral density related to defects is of $1/f$ type and its magnitude was found to be proportional to the square of the DC forward current at low injection levels. It has been established that samples showing low noise feature high-conversion efficiency. It has also been found out that there is a strong correlation between the sample initial-condition noise and the efficiency after 5000 h of combined stressing. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

We have studied a total of 20 solar cells, which were manufactured from silicon single crystals. The wafers were of circular form, of a diameter of 100 mm and a thickness of 360 μm. For the purpose of accelerated ageing, the samples were subjected simultaneously to a higher temperature, namely 400 K, and an electric field, corresponding to a voltage of 3 V applied in reverse direction to the cells.

The sample I–V characteristics and the noise parameters were measured before sample stressing and, subsequently, after 200, 500, 1000, 2000, 3000 and 5000 stressing hours.

In order to assess the suitability of noise parameters for the quality, reliability and service life testing, correlation between the initial parameters and those after 5000 h of stressing was evaluated.

2. Quality and reliability indicators

The idea to use noise measurements to electronic device technology analysis, device diagnostics and reliability forecast has been addressed by several researchers, such as, Van der Ziel and Tong [1], Vandamme et al. [2], Savelli et al. [3], Sikula et al. [4], Jones [5], Konczakowska [6].

A new specialisation—reliability physics—has arisen in this way, focusing on the identification of failure modes and mechanisms as the main sources of problems related to quality assessment and reliability prediction.

The actual reliability of electronic devices is usually lower than the maximum theoretical reliability, depending on the actual manufacture standard. This discrepancy may be due to irregularities in manufacturing processes. It is well known that most failures occurring in the flat region of the "bathtub curve" result from latent defects which have arisen during the device manufacture processes or operating life. The sensitivity of the excess electrical noise to this kind of defects is the main reason for using noise as a diagnostic and prediction tool in reliability physics for the semiconductor devices lifetime assessment.

Generally speaking, there are two kinds of noise. To the first kind belong thermal, shot and $1/f$ noise. These

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are called the fundamental kinds of noise. To the other kind belong low frequency excess noise types, such as flicker noise, burst noise, multiplication noise, generation–recombination noise and random telegraphic signal noise [7,8]. As is well known, the noise spectral density increases with stress and damage, varying substantially over identical device ensembles, being therefore not of fundamental nature.

Usually, the excess noise, generated by the excess current, has a $1/f$-type spectral density. Occasionally, the g–r noise, created by burst processes, is observed [9], too.

Qualitative characterisation of the $1/f$ excess noise can be carried out using the generalised Hooge's formula

$$S_I = F_Q I^2/f, \tag{1}$$

where S_I is the current noise spectral density, f, the frequency, I, the device current and F_Q, a proportionality constant (quality factor). This constant is being extensively used to characterise the device structural perfectness. For homogeneous samples, $F_Q = \alpha/N$. Theoretical values of α calculated from Hooge's theory, range typically from 10^{-9} to 10^{-8}. The quantity N in Hooge's formula is the total number of charge carriers in the sample. In the generalised form, N denotes the total number of fluctuators, which are contributing to the noise generation.

In our investigations, the measurable quantity to be used for quality and reliability testing is the ratio of $1/f$ noise current spectral density multiplied by frequency to the forward current squared. It will be used as an indicator of sample quality and reliability. It is given as

$$F_Q = S_I f/I^2. \tag{2}$$

In luminescent diodes, power diodes and solar cells, the current noise spectral density was found to be a quadratic function of the forward current in the low injection region. Typically, the excess current is a dominant current component in this region.

2.1. Maximum noise voltage spectral density across load resistance

Since the noise voltage across the load resistance is a measurable quantity, the testing procedure is based on the load resistance noise voltage data collection. The highest resolution of the current noise spectral density is obtained for the current values corresponding to the power matching condition. The ratio of the total measured noise to the background noise has a maximum value at this point.

This noise characteristic measured across the load resistance versus the forward bias has its extreme value if a dynamic resistance R_D of a p–n junction under test is equal to the load resistance R_L. The curve maximum shifts to a lower forward voltage region when the load resistance increases.

The measurable quantity is the noise voltage V_N across the load resistance R_L. The voltage power spectral density S_V is given by

$$S_V = \frac{V_N^2}{\Delta f}, \tag{3}$$

where Δf is the bandwidth of the measuring apparatus.

The current power spectral density S_I can be calculated as

$$S_I = \frac{S_V}{R_P^2}, \tag{4}$$

where

$$R_P = \frac{R_D R_L}{R_D + R_L}, \tag{5}$$

R_D is the p–n junction dynamic resistance, for which it holds and can be expressed as $R_D = 1/\beta I_F$, where $\beta = q/nkT$.

In low injection mode, the load resistance $R_L < 1/\beta I_F$. Putting $\beta = 20\ \mathrm{V}^{-1}$ and $R_L = 100\ \Omega$, the low injection current region extends up to $I_F < 5 \times 10^{-4}$ A. In the low injection region, the current noise spectral density is given by the following expression:

$$S_I = \frac{S_V}{R_L^2}. \tag{6}$$

The voltage noise spectral density across the load resistance will reach a maximum value, S_{VM}, if the noise source internal resistance equals the load resistance (in low-frequency region).

Noise characteristics were measured by a standard digital measuring set-up in a frequency range from 1 to 10^5 Hz. Fig. 1 shows the electronic circuit used to measure the noise characteristics of solar cells samples. A DC voltage from a DC power supply is applied across points 1 and 2. Resistances R_1 and R_2 and capacitors C_1 and C_2 are used to suppress spurious effects of the measuring equipment. The load resistance R_L has been chosen to be 100 Ω. The noise voltage to be analyzed passes through a coupling capacitor C_3 between points 3 and 4 to be fed into the input of Unipan 233-7 low-noise pre-amplifier, subsequently processed and recorded.

The reliability indicators are based on the transport mechanism of charge carriers in forward and reverse

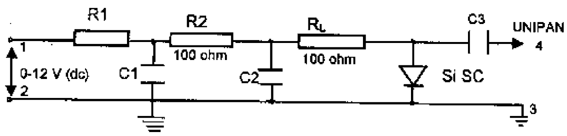

Fig. 1. Circuit diagram of a solar cell sample.

directions [9]. In the forward bias mode the voltage V_{R1} for a specified current of $I_{F1} = 10^{-3}$ A is used. The basic transport mechanisms involved are generation–recombination, diffusion, high injection, Zener and avalanche breakdown. *I–V* curves of p–n junction devices with these transport mechanisms are referred to as ideal ones. Additional charge carrier transport is detected in many p–n junction structures, resulting in an excess current.

3. Experimental results and discussion

3.1. I–V characteristics

The *I–V* characteristics were measured on all devices. For example, *I–V* characteristic of sample nos. 202 and 212 for forward and reverse directions are shown in Figs. 2–4. Sample no. 202 represents good and no. 212, poor quality devices. The straight-line-like shape at low DC voltage as shown in Figs. 3 and 4 in log–log scale makes it evident that the p–n junctions of both samples are shunted by a shunt of a resistance R_{SH}. For no. 202 sample, the shunt $R_{SH} = 80\ \Omega$ in forward direction and $R_{SH} = 1400\ \Omega$ in reverse direction. For no. 212 sample, these shunt resistors are 3300 Ω and 7 kΩ, respectively.

The deflection of the *I–V* characteristics from β slope appearing at higher voltages (Fig. 2) makes it possible to determine the series resistance R_S, whose value is about 0.1 Ω.

The total diode current may be expressed in the following form:

$$I = I_0\{\exp[q(V - IR_S)/kT] - 1\} + (V - IR_S)/R_{SH}. \quad (7)$$

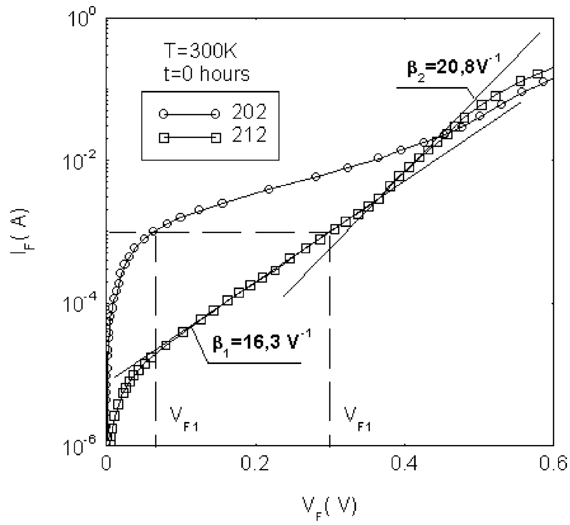

Fig. 2. *I–V* characteristic for nos. 202 and 212 solar cells in forward bias direction.

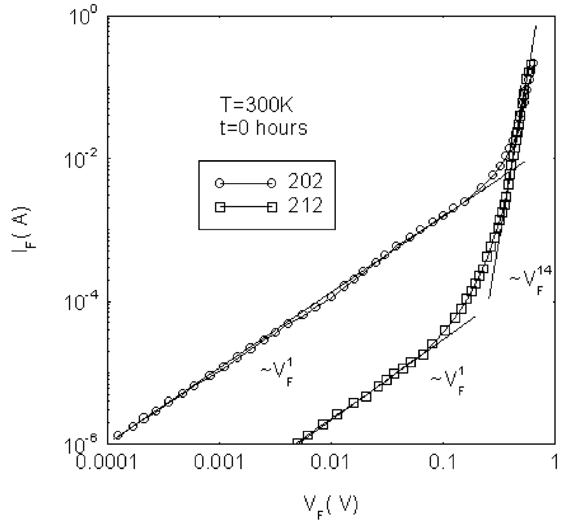

Fig. 3. Plot of $\log I$ versus $\log V$ for nos. 202 and 212 solar cells in forward bias direction.

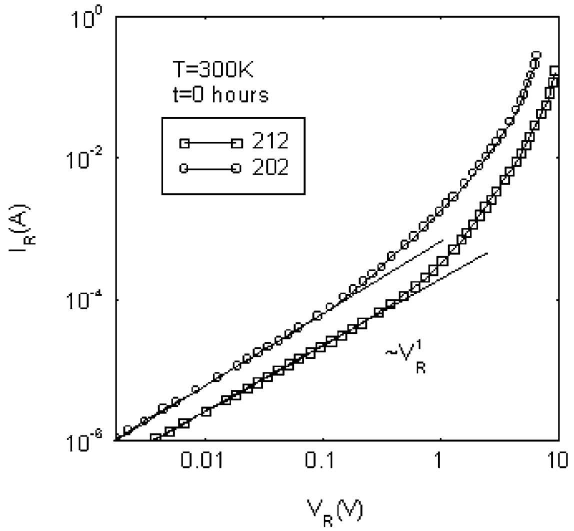

Fig. 4. Plot of $\log I$ versus $\log V$ for nos. 202 and 212 solar cells in reverse bias direction.

The whole current is a sum of the current flowing through the shunt resistor R_{SH}, the generation–recombination current and the diffusion current.

If the density of charge carriers injected into the quasi-neutral region exceeds the majority carrier density, the junction is operated in high-injection mode.

Fig. 2 demonstrates the applicability of V_{F1} parameter. V_{F1} is the forward voltage at which the diode forward current $I_{F1} = 10^{-3}$ A. The difference between poor samples (represented by sample no. 202) and good ones (represented by sample no. 212) will be easily seen at this current.

3.2. Noise

The excess noise is of $1/f^m$ type with $m \approx 1$ as is shown in Fig. 5, where S_V is the noise spectral density measured across the load resistance $R_L = 100\ \Omega$.

The current noise spectral density is proportional to the square of the forward current in the region where Ohm's law is valid (Fig. 6). Similar results are obtained in reverse direction (see Fig. 7).

The quality factor, $F_Q = fS_I/I^2$, in forward direction is equal to 1.5×10^{-9} for sample 202 and to 1.2×10^{-10} for sample 212, for current $I = 10^{-3}$ A.

In Fig. 8, we are presenting the noise voltage spectral density versus applied DC voltage plots for nos. 202 and 212 samples. The voltage was picked up across the load resistance $R_L = 100\ \Omega$. The mean frequency was 1 kHz, the bandwidth equalled 20 Hz and the samples temperature was 300 K. Sample no. 202, which exhibits a pronounced excess current component, features an excess noise spectral density which is more than one order higher than that of no. 212 sample.

In the power match condition, the spectral density S_{VM} of no. 202 sample has a maximum value of $S_{VM} = 5 \times 10^{-15}\ V^2\,Hz^{-1}$ at a forward voltage of $V_F = 0.22$ V, whereas that of sample no. 212 is $S_{VM} = 1.5 \times 10^{-16}\ V^2\,Hz^{-1}$.

3.3. Reliability

We have analyzed the hypothesis of a correlation potentially existing between the noise quality parameter,

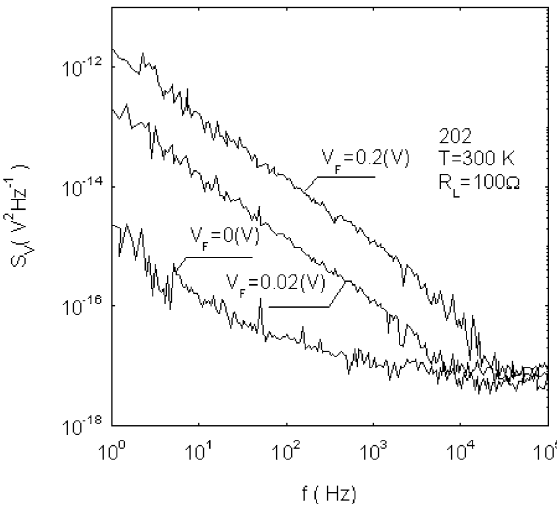

Fig. 5. The noise spectral density versus frequency for no. 202 sample.

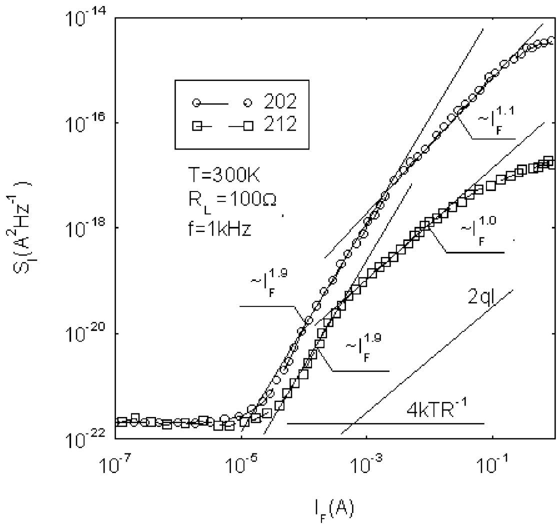

Fig. 6. The current power spectral density as a function of forward current for nos. 202 and 212 samples.

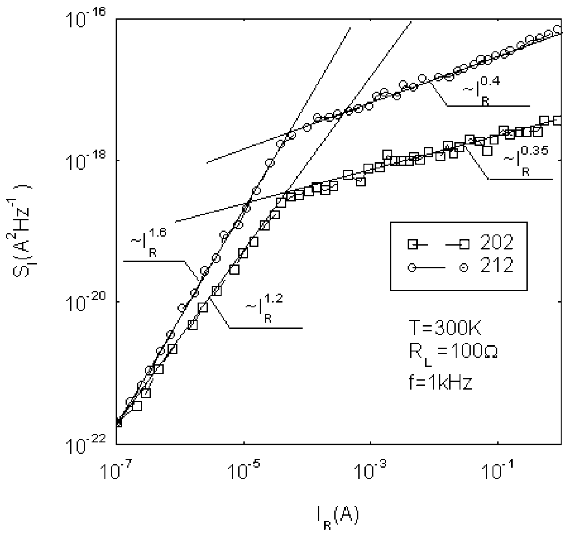

Fig. 7. The current power spectral density as a function of reverse current for nos. 202 and 212 samples.

S_{VM}, and the transport characteristic based quality parameter, V_{F1}. The results of this study are presented in Fig. 9, where the pre-stress correlation is shown for the entire ensemble of samples under study, i.e., before the high-temperature and electric-field stressing was applied. Fig. 6 illustrates the $S_I = f(I_F)$ plot as calculated from Eqs. (4)–(6) for nos. 202 and 212 samples. It is apparent that the S_I versus current plot follows the square law in the generation–recombination current region (up to about 10^{-3} A) whereas it is linear for the diffusion current component. It is evident that both samples feature a

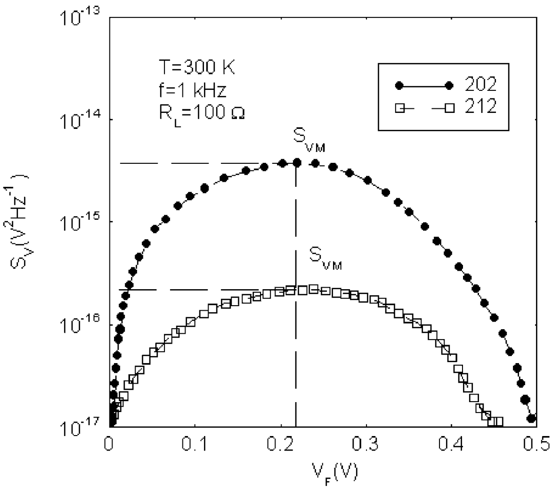

Fig. 8. The noise spectral density as a function of forward voltage.

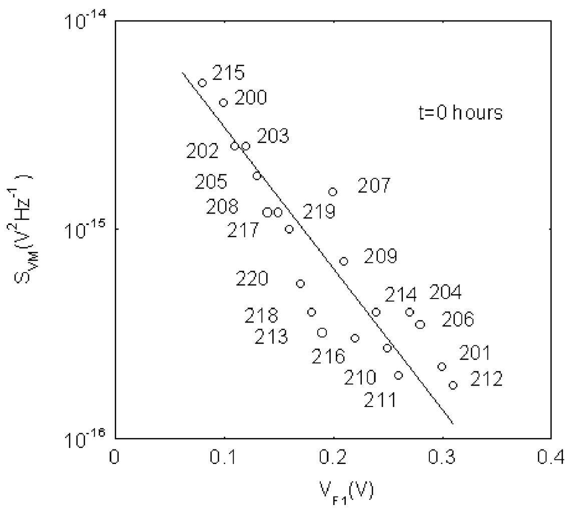

Fig. 9. The correlation between voltage spectral S_{VM} density and parameter V_{F1}.

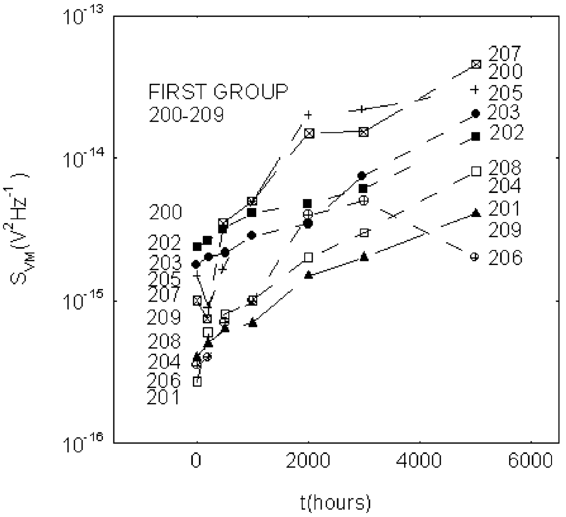

Fig. 10. Evolution of S_{VM} during 5000 h of stressing (sample nos. 200–209).

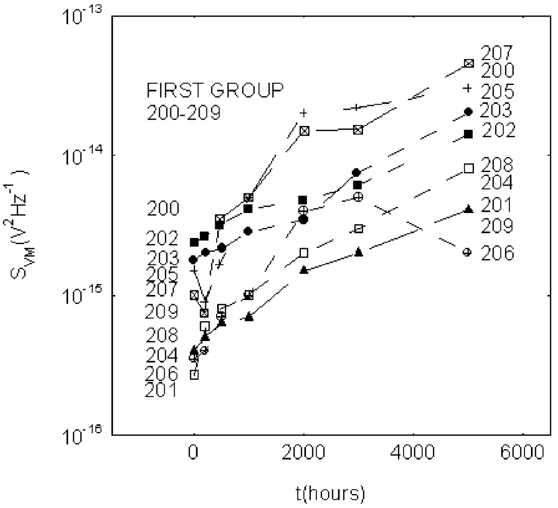

Fig. 11. Evolution of S_{VM} during 5000 h of stressing (sample nos. 211–220).

considerable excess noise component, which exceeds the thermal noise ($4kTR^{-1}$) and shot noise ($2qI$) spectral densities. Samples with a high-excess current component feature a low V_{F1} parameter and a high-noise spectral density. The S_I versus I_R plot is demonstrated in Fig. 7.

Figs. 10 and 11 are presented to illustrate the variations of the S_{VM} parameter during the high-temperature (400 K) and electric-field ($V_R = 3$ V) stressing period. This quantity decreases during the first 200 h (burn-in period). Subsequently, a period of an almost monotonous growth of this parameter follows, thus characterizing a gradual quality deterioration of the samples under test.

In Fig. 12 the correlation between S_{VM} and solar effectiveness parameters Eff after 5000 h of stressing is shown. The correlation factor is growing up with the stressing time up to a value of 0.82 after 5000 h. This is why we are recommending to apply the noise parameter, F_Q, to the solar cell service life prediction and reliability appraisal.

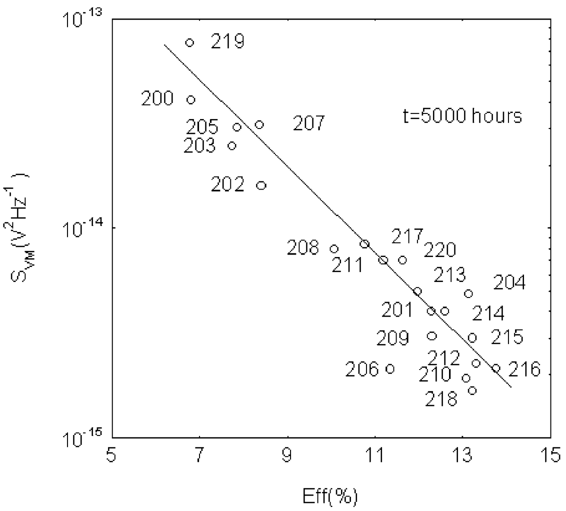

Fig. 12. The correlation between spectral voltage density S_{VM} and solar effectivness parameter Eff after 5000 h of stressing.

4. Conclusion

In the course of these studies, a total of 20 single-crystal silicon solar cells were subjected to accelerated tests. The samples were stressed by an increased temperature and an electric field during 5000 h.

From the measurement results it follows that the noise spectral density related to defects is of $1/f$ type and the current noise spectral density is proportional to the square of DC current in the low-injection mode. Samples with lower noise have higher efficiency. The average value of the noise spectral density of the entire ensemble increases with stressing time. Our screening parameter F_Q was used to evaluate the correlation between the spectral density and the light conversion efficiency. It has been found out that there is a strong correlation between the initial-state noise and the conversion efficiency after 5000 h of combined stressing.

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1/*f* NOISE AS A SENSITIVE PARAMETER IN THE LIFE PREDICTION TESTING OF PHOTOVOLTAIC MODULES

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Summary

The magnitude of the series resistance of photovoltaic modules is a measure of the quality of the modules and an increase in this resistance leads to power loss in the modules. However, as the series resistance amounts to only 1 - 10 Ω, changes in the resistance are difficult to detect. It is well known that at high forward currents the 1/*f* noise in p–n diodes is sensitive to changes in the series resistance of the diodes. Noise measurements on BPX 47 solar cell modules confirmed the 1/*f* character of the noise of these modules. The correlation between the series resistance and the 1/*f* noise at 1 kHz and 500 mA forward current was then measured; it appears that the 1/*f* noise is extremely sensitive to the magnitude of the series resistance. Therefore, 1/*f* noise is a sensitive parameter in degradation measurements and thus in life prediction tests of these modules.

1. Introduction

The large-scale use of photovoltaics depends on the cost and reliability of the photovoltaic cells, including their interconnections. As the contact metallization on the semiconductor surface and the interconnections between the cells are prone to environmental influences, groups of cells are encapsulated in modules to increase their reliability. However, one of the causes of reduction in the lifetime of modules is still the gradual degradation of these electrical contacts and interconnections [1]. As a result of this degradation, the series resistance increases with a consequent gradual increase in power loss in the module.

Measurement techniques and instruments suitable for the life prediction testing of photovoltaic arrays have been evaluated [2]. The series resistance does not appear to be a sensitive measure of the gradual degradation of contacts. 1/*f* noise was suggested as an alternative [2] because it had been

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proved to be a sensitive measure of the contact resistance of diodes. Although in corresponding measurements of photovoltaic cells $1/f$ noise increased significantly with high humidity stressing, this increase failed to show a correlation with changes in the series resistance. These negative results could not be satisfactorily explained and therefore other sources of noise were held to be responsible.

Recently, the contributions of different sources to the composition of $1/f$ noise have been clarified [3]. With this insight, it was thought to be appropriate to try $1/f$ noise anew as a sensitive parameter of the degradation of photovoltaic modules. Therefore, measurements of $1/f$ noise were carried out on some old and new modules. The results were compared with earlier experiments on p–n junctions.

2. Distinction of $1/f$ noise sources

A possible way of distinguishing the contributions of the different sources of $1/f$ noise in p–n diodes has been given by Kleinpenning [3]. He has shown that the different sources of $1/f$ noise can be dominant in different regions of the current density. For very low forward currents in p–n junctions, the current and its inherent noise are due to the generation–recombination of current carriers at generation–recombination centres in the space charge region of the junction [4]. At higher forward currents the diffusion current in the base becomes dominant. The power of the noise is then due to the $1/f$ noise in the diffusion current. In this higher current region a third type of $1/f$ noise, *i.e.* $1/f$ resistance noise, can become dominant.

Similar noise behaviour is shown by a photovoltaic cell in the dark because of its inherent diode. The noise of a photovoltaic cell is measured as fluctuations in the voltage across the cell. These fluctuations in voltage are linked to the fluctuations in current by the forward current–voltage (I–V) characteristic of the cell. According to the electrical circuit diagram of the photovoltaic cell given in Fig. 1, the forward I–V characteristic in the dark can be represented by

$$I = I_0 \left[\exp\left\{ \frac{q(V - IR_s)}{nkT} \right\} - 1 \right] \tag{1}$$

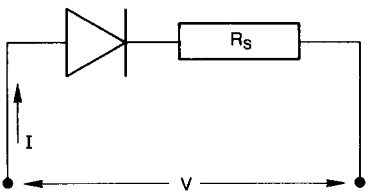


Fig. 1. Electrical circuit diagram of the photovoltaic cell (the series resistance R_s represents the total electrical resistance of the cell including the contact resistance).

where I is the forward current, V the forward voltage, R_s the series resistance including the electrical contact resistance, I_0 the saturation current (constant), q the elementary charge, k Boltzmann's constant, T the temperature and n an ideality parameter.

Three regions can be distinguished in the forward I–V characteristic of the cell because of their different slopes. These slopes become apparent on differentiation of eqn. (1):

$$\frac{\mathrm{d}V}{\mathrm{d}I} = \frac{nkT}{q(I+I_0)} + R_s \tag{2}$$

I_0 will be neglected, since in our measurements $I \gg I_0$.

At low currents the first term on the right-hand side of eqn. (2) determines the slope of the I–V characteristic. At very low currents, $n = 2$ because both electrons and holes alike contribute to the current in the space charge region of the junction. At higher currents, $n = 1$ and at much higher currents the second term on the right-hand side of eqn. (2) can become dominant. These current regions in the I–V characteristic coincide with the current regions distinguished in the noise of the cells. As a consequence, the voltage noise also has three regions which can be distinguished by the current dependence of the voltage noise, as shown in Section 3.

3. Calculation of $1/f$ voltage noise

$1/f$ noise in semiconductors and metals has been described by Hooge [5] by an empirical relation. This relation has been extended to p–n diodes by Kleinpenning [3]. As a result the $1/f$ noise can be described in terms of the current noise and the resistance noise.

In the generation–recombination current region

$$S_I = 2qI\,\frac{\alpha_1}{3f\tau} \tag{3}$$

and in the diffusion current region

$$S_I = 2qI\,\frac{\alpha_2}{8f\tau} \tag{4}$$

where S_I is the spectral density of the short-circuit current noise, α_i a constant of the order of 10^{-3}, f the frequency and τ the lifetime of the relevant current carriers. In the current region where $1/f$ resistance noise becomes dominant [5]

$$S_{R_s} = {R_s}^2\,\frac{\alpha_3}{fN} \tag{5}$$

where S_{R_s} is the spectral density of the $1/f$ resistance noise and N is the number of free carriers.

This $1/f$ resistance noise is due to fluctuations in the free-carrier mobility of the semiconductor and the metal of the contacts [3]. The relation given by eqn. (5) is valid only when the current is homogeneously distributed. For non-homogeneously distributed currents the number of free carriers contributing to the current is less than N. In this situation, N has to be replaced by N_{eff}.

The spectral density of the open-circuit voltage fluctuations can be calculated as

$$S_V = S_I Z^2 + I^2 S_{R_s} \tag{6}$$

where Z is the differential impedance of the diode ($Z \approx nkT/qI$ (see eqn. (2))).

In the determination of Z the capacitance of the diode was neglected. At low currents and high frequencies this capacitance causes the appearance of a first-order cut-off frequency in the spectra. This cut-off frequency is inversely proportional to the product of the capacitance and the differential resistance [3].

With the help of eqns. (2) - (6) we obtain in the generation–recombination current region

$$S_V = \frac{2(2kT)^2}{qI} \frac{\alpha_1}{3f\tau} \tag{7}$$

and in the diffusion current region

$$S_V = \frac{2(kT)^2}{qI} \frac{\alpha_2}{8f\tau} + I^2 S_{R_s}$$

$$= \frac{a}{I} + bI^2 \tag{8}$$

When the spectral density S_V measured at one frequency is plotted as a function of the forward current I, three regions are distinguishable: the generation–recombination current region; the diffusion current region; the current region dominated by series resistance.

In the generation–recombination current region the spectral density shows an I^{-1} dependence. It also shows an I^{-1} dependence in the diffusion current region. However, the values of the spectral density will be lower in this region because the lifetimes of the then prevalent current carriers are longer. When at higher current levels the series resistance term becomes dominant, the spectral density will show an increase proportional to I^2.

Consequently, the region of the spectral density of the open-circuit voltage fluctuations which shows an I^2 dependence and still has a $1/f$ character can be ascribed to the series resistance of the cell. For a photovoltaic module with N series-connected cells we have in the diffusion current region (*cf.* eqn. (8))

$$S_V = \sum_{i=1}^{N} \left(\frac{a_i}{I} + b_i I^2 \right)$$

$$= \frac{A}{I} + BI^2 \tag{9}$$

where $A = \Sigma a_i$ and $B = \Sigma b_i$.

Thus, when the open-circuit voltage noise of a photovoltaic module has a $1/f$ character and is proportional to I^2 at high current levels, the noise results from the series resistances of all the cells. In this situation the power spectral density of the open-circuit voltage noise can be ascribed to the series resistance of the photovoltaic module.

4. Results and discussion

Measurements were performed on several BPX 47 photovoltaic modules that were 9 years old. The series resistance of the modules was determined in the forward I–V characteristic in accordance with eqn. (2). A typical example of a measured I–V characteristic is given in Fig. 2, where the different regions can be distinguished clearly.

The noise voltage of the modules was measured in the experimental set-up shown in Fig. 3. The measured voltage U_{xy} was amplified, filtered and squared before being recorded. The results were corrected for the voltage drop across the resistances in the circuit (Fig. 4). The correction factor

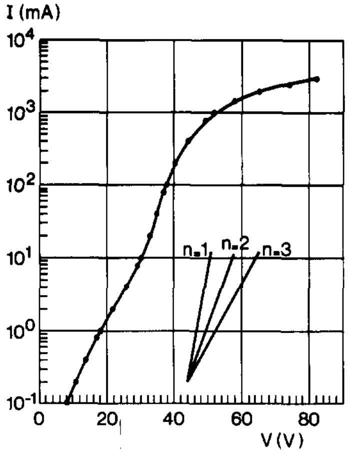


Fig. 2. Typical forward I–V characteristic of a BPX 47 module in the dark (the module contains 64 cells).

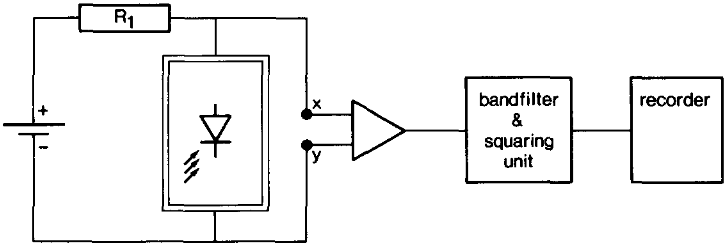
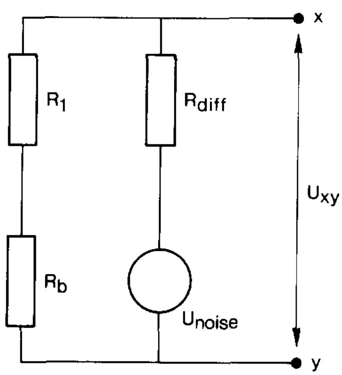


Fig. 3. Circuit diagram for the measurement of the noise of photovoltaic modules.



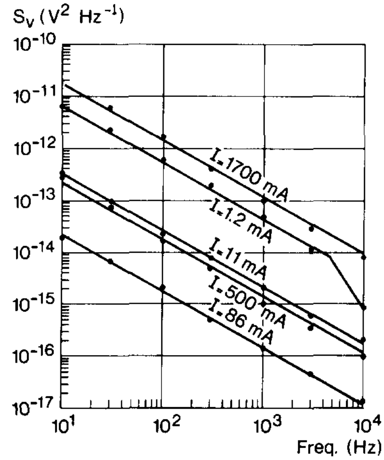


Fig. 4. Equivalent circuit diagram for the determination of the noise voltage of a photovoltaic module (R_1, resistance (see Fig. 3); R_b, internal resistance of the battery; R_{diff}, differential resistance of the photovoltaic module as defined by eqn. (2); U_{noise}, the noise voltage of the photovoltaic module; U_{xy}, measured noise voltage).

Fig. 5. Noise spectra measured at various currents.

$$\left(\frac{R_b + R_1 + R_{diff}}{R_b + R_1}\right)^2 \tag{10}$$

is derived from the relation

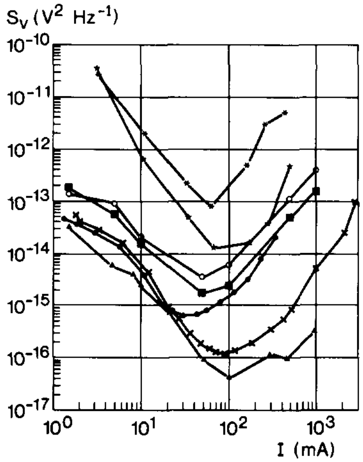
$$U_{xy}^2 = U_{noise}^2\left(\frac{R_b + R_1}{R_b + R_1 + R_{diff}}\right)^2 \tag{11}$$

To obtain the spectral density of the noise, the power of the noise was divided by the bandwidth of the filter.

Measurements of the spectral density of the noise of the photovoltaic modules as a function of frequency show typical $1/f$ character (Fig. 5). At low currents (about 1 mA) the cut-off frequency which results from the capacitance of the module is perceptible.

Once the $1/f$ character of the noise spectra had been established, this $1/f$ noise was measured as a function of the forward current in the module at a frequency of 1 kHz. Typical results are given in Fig. 6. From these results an I^2 dependence of the $1/f$ noise in the high current regions is apparent in accordance with eqns. (8) and (9).

As can be seen in Fig. 7, the $1/f$ noise in the high current region correlates with the series resistance of the modules. This figure shows that the $1/f$ noise increases by more than two orders of magnitude when the series resistance increases by a factor of 2. This sensitivity is in accordance with the findings of $1/f$ noise in diodes. Small point contacts give rise to a sensitivity proportional to R_s^5 [6]. Even this sensitivity can increase if the current density is inhomogeneous, since this causes a decrease in the number of effective current carriers.



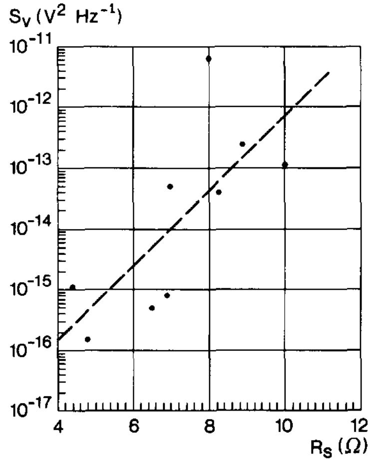


Fig. 6. The spectral density of the voltage noise of photovoltaic modules measured at 1 kHz as a function of forward current.

Fig. 7. The spectral density of the voltage noise of the photovoltaic modules measured at 1 kHz and 0.5 A related to their series resistances.

In accordance with the data of Fig. 7 and the detection limit of 8×10^{-19} V^2 Hz^{-1} in our experiments, the I^2-related noise of a module with a series resistance of 1 Ω will perhaps be just measurable. Measurements performed on a new BPX 47A module show an I–V characteristic similar to that of the old BPX 47 modules. The series resistance was measured to be 1.6 Ω. This low value probably arises because the new module has had the advantage of better manufacturing technology and hence has better contacts and interconnections. The low series resistance means that the R_s-dominated region in the spectral density–current characteristic will occur at higher currents. Owing to current heating of the module the forward current in the dark is limited to 1 A. As a result of this limit the R_s-dominant part of the current region could not be reached (Fig. 8).

In Fig. 8 there is a large region in which the spectral density S_V of the voltage noise is proportional to I^{-2}. This region can also be identified in some of the curves in Fig. 6. The S_V curves should be described by eqns. (7) and (8), in which there is no region of I^{-2} proportionality. This discrepancy between the I^{-2} measured dependence and the I^{-1} theoretical dependence is not fully understood. However, it is possible that $1/f$ noise generated in the space charge region by generation–recombination currents can be dominant when the I–V characteristic is determined by diffusion currents in the base. This will give a spectral density of the voltage fluctuations with an $I^{-1.5}$ proportionality. Technological factors may be responsible for a further change to I^{-2} proportionality. These factors may play an important role as it has recently been established that carefully manufactured small diodes show only I^{-1} proportionality [3]. A discrepancy reported in ref. 7, where the value given for the noise is too high in comparison with the value calculated

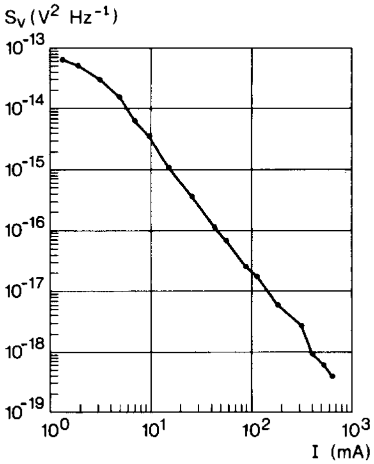


Fig. 8. The spectral density of the voltage fluctuations of a new BPX 47A photovoltaic module measured at 1 kHz as a function of forward current (series resistance of the module, 1.6 Ω).

in accordance with eqns. (7) and (8), has been explained on the basis of inhomogeneities in the junction.

5. Conclusions

A correlation was established between $1/f$ noise in the dark at high forward currents and series resistance for photovoltaic modules. In this current region, $1/f$ noise is extremely sensitive to the magnitude of the series resistance. Therefore, $1/f$ noise seems to be very suitable as a sensitive parameter in the life prediction testing of contact metallization. For low series resistance the limits of applicability are imposed by the noise of the first amplifier in the measuring system and the current heating of the module.

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