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Measurement of $1/f$ noise and its application in materials science

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Abstract

This is a review of the measurement of $1/f$ noise in certain classes of materials which have a wide range of potential applications. This includes metal films, semiconductors, metallic oxides and inhomogeneous systems such as composites. The review contains a basic introduction to this field, the theories and models and follows it up with a discussion on measurement methods. There are discussions on specific examples of the application of noise spectroscopy in the field of materials science.

1. Introduction

The study of fluctuations in physical properties of condensed matter has been an active area of research for decades. These studies have led to important insights into the physical phenomena that are associated with fluctuations. The most visible activity in this field is definitely the ubiquitous $1/f$ noise. The name $1/f$ noise arises because large classes of fluctuations in condensed matter systems show a power spectrum ($S(f)$) that has $1/f^{\alpha}$ frequency dependence with $\alpha \sim 1$. The physical systems that display these power spectra can be electrical noise in a metal film carrying a current, or even the heartbeats. The generality of this type of noise has often led to very general theories or models that go beyond the realities of a given physical system. It is however becoming clear that there is no general explanation of $1/f^{\alpha}$ noise and it can arise from different physical processes. These processes may have certain generic attributes of relaxation in them that can lead to such a $1/f^{\alpha}$-type power spectrum. It is important that the details of a physical system be examined before one would hope to understand the origin of $1/f$ noise.

$1/f$ type noise in most condensed matter systems arises because of relaxation of defects or groups of defects whose dynamics has a finite relaxation time. In essence noise experiments couple to these dynamics and thus can be a viable tool to study such defects and characterize them. While most other measurements pick up average properties, existence of noise presupposes existence of statistical distribution in the fluctuating quantities. It is thus a unique and sensitive tool that can give us information on the underlying statistics of defects and the relaxation phenomena that give rise to the noise. The main issue is how to make this unique and sensitive tool useful in the study of materials science. The aim of the present review will be to discuss some of the experimental attempts that have contributed in this direction.

The review will focus on those aspects of $1/f$ noise where we think that it can be used as a tool in materials research. This will limit us to conductivity noise or excess noise, which occurs in a current carrying conductor in addition to the thermal noise or Nyquist noise. This review will include studies on metallic systems, semiconductors, metallic oxide systems like high T_c superconductors and colossal magnetoresistive (CMR) manganites and inhomogeneous systems like composites. In recent years, particularly in the last decade and a half, the field has matured both through clean measurements and through infusion of new concepts. An important application of $1/f$ noise is in the field of reliability of metallic films and interconnects; particularly those used in VLSI circuits. In the field of rare-earth manganites noise is a useful probe to investigate such exotic phenomenon as electronic phase separation. It has provided valuable insights into the study of driven-pinned systems such as charge density wave system and flux lattice in superconductors. Further progress in this field depends on imaginative application of the probe in well-defined systems and quantitative analysis of the data to elucidate the mechanism of noise in a specific system. Correlation of the noise spectroscopy with other properties, particularly the structural and microstructural characterization, needs to be done more rigorously. The investigation of the non-Gaussian power spectra and statistics of the voltage jump, can be added to the usual

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measurement of the power spectrum $S(f)$. This will make noise measurements even more informative. A very useful noise probe in characterizing magnetic alloys is Barkhausen noise. Since this is strictly not in the domain of $1/f$ noise this is not in the scope of the review.

This is not an exhaustive review of the theories of $1/f$ noise. We refer to some of the existing classics that have discussed the general aspects of $1/f$ noise [*1,**2–**4]. Nevertheless, to make the review self-contained, some of the basic definitions and concepts to be used in the later part are included in the introduction. Some of the experimental aspects of measurements of noise in condensed matter system have also been discussed. In the rest of the review specific examples have been discussed to elucidate the application of noise in investigation of materials.

2. Algebra of noise

Certain common algebraic language is used to define and quantify noise. This is introduced in this subsection and will be used whenever required in the review. In general, the fluctuating quantity (like an electrical voltage) is recorded in the time domain. The power spectrum $S(f)$ quantifies the noise in the frequency domain. If $X(t)$ is the fluctuating quantity with a zero mean (i.e. $\langle X(t)\rangle = 0$), the power spectrum is expressed as the amplitude squared of the Fourier-transformed (FT) signal:

$$S(f) = \underset{T\to\infty}{Lt}\left(\frac{1}{2T}\right)\left|\int_{-T}^{T} \mathrm{d}t\, X(t)\, \mathrm{e}^{-i2\pi ft}\right|^2 \tag{1}$$

According to the Wiener–Khintchine theorem [5], $S(f)$ is the FT of the autocorrelation function $C(\tau)$ defined as:

$$C(\tau) = \underset{T\to\infty}{Lt}\left(\frac{1}{2T}\right)\int_{-T}^{T} \mathrm{d}t\, X(t+\tau)X(t) \tag{2}$$

It is interesting to note that to have the power spectrum of the inverse power law form, $S(f) \propto f^{-\alpha}$, the autocorrelation function $C(\tau)$ should have the form, $C(\tau) \propto |\tau|^{\alpha-1}$. This would imply that with $\alpha \leq 1$, there is a long time correlation in the system.

The spectral power becomes frequency dependent because there is a finite relaxation time associated with the fluctuating variable. This relaxation can be quantified by the relaxation function $\varphi(t)$. The power spectrum in that case is given as:

$$S(f, T) = C\int_{-\infty}^{\infty} \mathrm{d}t\, \mathrm{e}^{-j2\pi ft}\varphi(t) \tag{3}$$

A common relaxation function is the Debye relaxation function with a single relaxation time τ so that $\varphi(t) \propto \mathrm{e}^{-t/\tau}$. In this case the power spectrum $S(f)$ is a Lorentzian given by:

$$S(f) \propto \frac{2\tau}{1+(2\pi f\tau)^2} \tag{4}$$

In Fig. 1(a), we give a sketch of $S(f)$ as a function of f for a given τ. In the specific graph shown in Fig. 1(a) the $\tau^{-1} = 1$ Hz. At the low frequency end for $f \ll \tau^{-1}$, $S(f) \to$ constant and at the high frequency end ($f \gg \tau^{-1}$), $S(f) \propto 1/f^2$.

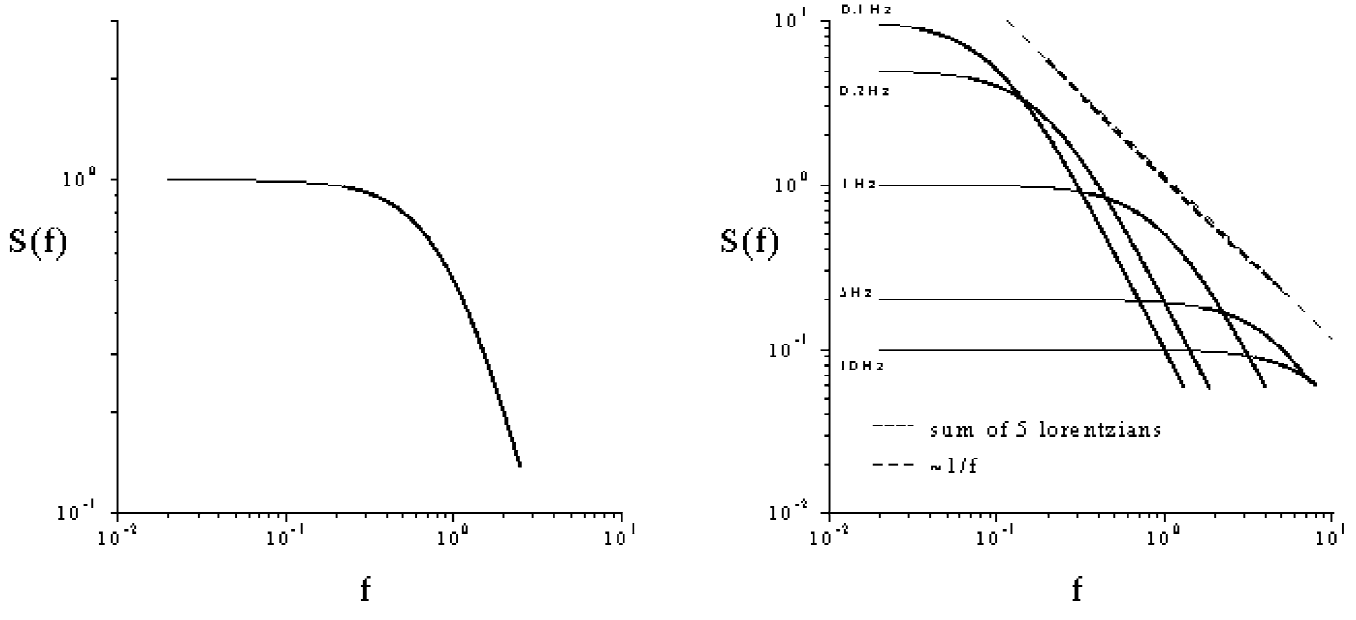

Fig. 1. (a) The Lorentzian power spectra of a single fluctuator ($\tau^{-1} = 1$ Hz). (b) Generation of a power law $S(f)$ from superposition of Lorentzians. In this case five Lorentzians have been used. τ^{-1} is marked in the graph.

In presence of a distribution of relaxation time the power spectrum is given as:

$$S(f) \propto \int_0^\infty d\tau\, F(\tau) \frac{2\tau}{1+(2\pi f\tau)^2} \quad (5)$$

where $F(\tau)$ describes the distribution. In Fig. 1(b) we have shown how a $1/f$-type $S(f)$ can be obtained by adding up few well-spaced Lorentzians. In the example shown in Fig. 1(b) the $1/f$ type $S(f)$ was built up by summing up five Lorentzians with 0.1 Hz$\leq\tau^{-1}\leq$10 Hz. In general, a distribution of the type $F(\tau) \propto \tau^{-\alpha}$ will give rise to power spectrum $S(f) \propto f^{-2+\alpha}$.

3. Types of noise

The type of electrical noise that one sees in a solid are generally of three distinct types [**4]:

(a) Nyquist noise
(b) Shot noise
(c) Excess noise

Nyquist noise (often known as Johnson noise or Thermal noise) arises from the Nyquist theorem [5] and in a resistor of value R kept at a temperature T, it shows up as white noise ($S(f)$ independent of f) of spectral power:

$$S_v(f) = 4k_B TR \quad (6)$$

In this case, the spectral power $S_v(f)$ is independent of the current through the resistor and is not dependent on the materials property of the resistor. Johnson noise does not distinguish a metal film resistor of resistance R from a carbon film resistor of the same resistance. Consequently, it is a not a useful tool except in cases where it can be a measure of the effective electron temperature.

The shot noise, which arises from discrete carrier motion in devices, is also white in nature. It appears as a fluctuating current with spectral dependence, $S_I(f)$, proportional to the value of charge carrier (q) and the current (I) through the device. It is given as:

$$S_I(f) = 2qI \quad (7)$$

Shot noise is a good indicator of the magnitude of the charge carrier. In general, the shot noise is visible at low temperatures when the thermal noise is low enough.

The noise, which is of particular interest to most of the materials science applications is the excess noise or the conductivity noise. This noise exists in a solid in addition to the thermal noise and shot noise. It is measurable when a given conductor is carrying a current. The spectral power of the voltage noise ($S_v(f)$) depends quadratically on the applied bias ($S_v(f) \propto v^2$). Due to the quadratic dependence of the spectral power on the bias, it increases and rises above the thermal noise only at a finite bias. This is noise has a power spectrum $S_v(f) \propto f^{-\alpha}$. When $\alpha \approx 1$, this is referred to as the '$1/f$ noise'. Often the spectral power contains discrete or narrow band noise adding to the broad $1/f$ feature. Since the spectral power contains information on the dynamics of defect motion or relaxation, it is a very useful tool in material characterization. An example of $1/f$ noise measured in heavily doped single crystal Si is shown in Fig. 2(b) [6]. This has been obtained from the time series of voltage fluctuation shown in Fig. 2(a).The quadratic dependence of the spectral power $S(f)$ on the bias V is shown in Fig. 2(c). The power spectrum $S(f)$ follows $1/f^{\alpha}$ with $\alpha \approx 1$. In the same graph we show the frequency independent background noise (measured) which is $\approx 4k_B TR$. One can see from Fig. 2(b) that $1/f$ noise becomes visible at frequencies <1 KHz. At higher frequency the $4k_B TR$ background can hide it unless sufficiently high current is passed to measure the noise. On the low frequency side the reported measurements are generally done down to 0.1 Hz. However, some measurements

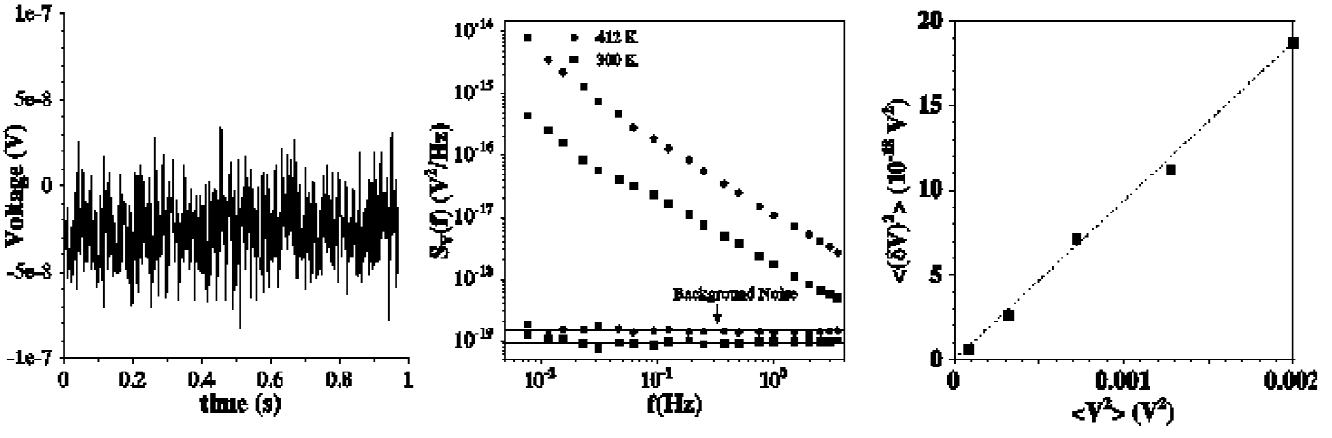

Fig. 2. (a) The experimentally observed time series (δV vs. t) during an experiment. (b) The power spectra $S(f)$ obtained from the time series shows the $1/f$ noise. The $4k_B TR$ white noise background is also shown. (c) The quadratic bias dependence of the spectral power density. (Data from Ref. [6]).

have been done down to 10^{-3} Hz even if they are not very common. There exists at least one report of measurements down to 10^{-6} Hz [7]. Such a low frequency measurement needs extremely good long term stability of temperature, and of course long sampling time ($\approx$50 h).

Often the noise is expressed as the rms fluctuation $\langle(\delta v^2)\rangle$. This has to be defined in a band width of measurement between f_{max} and f_{min} so that

$$\langle(\delta v)^2\rangle = \int_{f_{min}}^{f_{max}} \mathrm{d}f\, S(f) \tag{8}$$

4. Theories of conductivity noise

In order to utilize the tool of $1/f$ noise spectroscopy for materials characterization one needs a theory that correlates the measured noise with features of the materials to be characterized. Table 1 gives a catalogue of some of the theories/models that have been proposed to explain $1/f$ conductivity noise in various materials. It has to be admitted that there is no general theory of $1/f$ noise in condensed matter. Nevertheless, there are models that can describe certain observations or measurements. It is also important that attention be given to the specifics of the materials in which noise have been studied before a model is used for it. We refer to some of the published references for a critical review of the mechanisms [**3,**4,*8].

An early work in this field [9] proposed a way to normalize the noise data (spectral power) in different systems showing $1/f$ noise. This model is based on the fact that noise is arising from the bulk of the solid. If the noise at a given spectral power arises from independent motion of N electrons within the solid then the spectral power $S(f)$ is expressed as:

$$S(f) = (1/N)\gamma_H \frac{V^2}{(f)} \tag{9}$$

where the constant γ_H is dimensionless if $S(f)$ is expressed in the unit of V^2/Hz. The constant γ_H, referred to as the Hooge's constant is often used as the measure of the noise magnitude. It is however not a universal number and depends on the purity of the material and presence of point as well as extended defects. Scaling by Hooge's relation and obtaining a frequency independent γ_H assumes that $S(f)$ is strictly $1/f$ (i.e. $\alpha = 1$). For other cases ($\alpha \neq 1$)γ_H is frequency dependent and has to be defined at the frequency at which it is measured. Caution needs be exercised in using the normalisation procedure expressed in Eq. (9) because if the noise source is not in the bulk it will give erroneous results for γ_H.

A particular model of noise has been proposed [*8] which is based on the basic idea that noise in a material arises due to mobility ($\mu_{lattice}$) fluctuation when the charge carrier (electrons) undergoes scattering from lattice phonon modes. In this model the source of fluctuation is the fluctuation in the phonon numbers or occupation of various modes. In this model the magnitude of the noise is proportional to the lattice mobility (i.e. $\gamma_H \propto \mu_{lattice}$). This model is sometime used in describing noise in pure semiconductors. In this model impurities play a limited role in $1/f$ noise.

The noise in a solid depends on its quality and purity. This makes noise spectroscopy an important tool. The use of $1/f$ noise in materials characterization is thus based on two ruling paradigms. They are: (a) The excess noise is a manifestation of the resistance (R) or conductance (G) fluctuation so that the relative mean square voltage fluctuation $\langle(\delta v(t))^2\rangle/\langle v\rangle^2 = \langle(\delta G(t))^2\rangle/\langle G\rangle^2$. This has been experimentally established [*10], (b) the noise has a defect origin, which has been experimentally established, notably by experiments on metal films [*11] as well as on semiconductors [12]. Most of the current theories/models that can be used for applications in materials science are based on the above two paradigms. In addition, a complete theory of noise, which can make noise a useful tool, should have three essential ingredients. These are (a) a clear identification of the fluctuation mechanism, (b) a coupling mechanism of electrons to the fluctuating species so that it can lead to conductivity fluctuations, and (c) dynamics of the fluctuation quantified through the relaxation function $\varphi(t)$ so that the spectral power $S_v(f)$ can be calculated. In view of the above benchmarking we would find that we have essentially two classes of theories/models.

The first class of models, like the Dutta–Horn (DH) model [**2,13], the Self Organized Criticality (SOC) model [14] or the diffusion model [15], show how the dynamics of fluctuation can arise and how it can be linked

Table 1

Model	Reference
McWhorter model	McWhorter in 'Semiconductor Surface Physics' (Ed. Kingston), University of Pennsylvania Press, Philadelphia (1957)
Hooge model	Hooge [*8,9]
Temperature fluctuation model	Voss and Clarke [*10]
Dutta–Horn (DH) model	Dutta and Horn [**2]
Universal Conductance Fluctuation (UCF) model	Feng et al. [*16]
Local Interference (LI) model	Pelz and Clarke [*17]
Self-Organized Criticality (SOC) model	Bak et al. [14]
Diffusion model	Fourcade and Tremblay [15]

to the observed power spectrum. These models are of generic nature and do not deal with specific defects, nor do they address the coupling mechanism. The second class of models like the Universal Conductance Fluctuation (UCF) [*16] or Local Interference (LI) model [*17] give a physical process of generating conductivity fluctuations from defect motion but do not provide an explicit theory about the dynamics of the defects and the power spectrum is added to it 'by hand'. A defect model that falls into this category is the model for generation-recombination (GR) noise [18] that is often found in semiconductors. It has been shown that a distribution of GR time arising from distribution of trap states near the conduction or valence band can also produce $1/f$ noise [19].

The DH model (which is a phenomenological model) is based on smeared activated kinetics that will give a distribution of relaxation time $F(\tau) \propto 1/\tau$, so that a power spectra of the type $1/f^{\alpha}$ is obtained with $\alpha \approx 1$. When the relaxation time $\tau \equiv \tau_0\ \mathrm{e}^{E/kT}$, where E is the activation energy, the spectral power as can be expressed through the following equations [13]:

$$S(f) \propto \int_0^{\infty} \mathrm{d}E D(E) \frac{2\tau_0\ \mathrm{e}^{E/kT}}{1 + (2\pi f \tau_0\ \mathrm{e}^{E/kT})^2} \tag{10}$$

It is envisaged that a distribution of the activation energy, $D(E)$, that is flat in the scale of $k_{\mathrm{B}}T$ will give the desired distribution so that $F(\tau) \propto 1/\tau$ for $\tau_{\max} \gg \tau \gg \tau_{\min}$ and $S_v(f) \propto f^{-}$ for the frequency range $\tau_{\max}^{-1} \ll f \ll \tau_{\min}^{-1}$. (It may be noted that even a distribution of the hopping rate τ_0^{-1} can give the desired power spectrum). The DH model, which is commonly used to analyze conductivity noise data (often without appreciating its content), has a very powerful prediction that can be used to check its validity. It establishes an explicit relation between the noise exponent α and the temperature dependence of the spectral power, as given below [13]:

$$\alpha(f, T) \approx 1 - \frac{[\mathrm{d} \ln S / d \ln T - 1]}{\ln(2\pi f \tau_0)} \tag{11}$$

If an experimental spectral power density is found to follow the DH model (as confirmed from the equation above), this simply implies that the fluctuation follows activated smeared kinetics. It does not give any information about the nature of the defect that would give rise to such kinetics. Very often, the activation energy distribution $D(E)$ is obtained from the observed temperature dependent power spectrum with certain approximations. Such a procedure to obtain $D(E)$ is valid if the noise indeed follows the DH model. This can be confirmed using Eq. (1) and the experimental data.

In the SOC model [14] the basic presumption is that the system is close to a critical behaviour and fluctuations around that occur involving system sizes at all length scales with a distribution of clusters given by

$$D(s) \approx s^{-\zeta} \tag{12}$$

where the exponent $\zeta \approx 1$ for $2D$ and ≈ 1.37 for $3D$ in certain models of SOC, if the life time of the fluctuation is related to the system size by the relation $t^{1+\eta} \cong s$ then the distribution of the life time $D(t)$ is given by

$$D(t) \approx \frac{s}{t} D(S(t)) \frac{\mathrm{d}s}{\mathrm{d}t} \approx t^{-((\eta+1)\zeta + 2\eta} \equiv t^{-\beta} \tag{13}$$

Such a distribution in the lifetime of fluctuation will give a spectral power density $S(f) \propto f^{-2+\beta}$. This model has been tested numerically [20] and also experimentally in the context of Barkhausen noise [21]. It appears that the power law distribution of the size of the fluctuating regions (referred to as avalanche size) is neither a necessary nor sufficient condition for generating $1/f$ noise. There is scope to test this theory in the context of the conductivity noise.

The UCF model [*16] is based on the same physical concepts that give rise to the phenomenon of weak localization in disordered metals [22]. This phenomenon arises due to coherent superposition of back-scattered electrons, and is quantum mechanical in origin. The conductivity fluctuation is very large because it is a sensitive function of the impurity positions whose small motion can change the pattern of the coherent superposition of the electronic wave function. The important parameter is the length scale L_{φ} over which the electron retains its phase coherence. At low temperatures and in disordered solids where the electron mean free path l_{e} (limited by the elastic scattering) is small, L_{φ} can be $\gg l_{\mathrm{e}}$. This is the condition under which the UCF can take place. Experiments on disordered metal films like Bi and Ag have shown that in disordered metals (weakly localized) the conductivity noise at low T indeed arises from the mechanism of UCF [*23].

The LI model [*17,*23] is based on the premise, that the resistivity tensor becomes anisotropic because of the interference of electrons scattered from structural defects like vacancies and interstitials (which are isotropic), this interference also makes the resistivity tensor dependent on the separation of the scatterers. This dependence on defect separation is more effective for separation of the order of few k_F^{-1}, and hence the name local interference. The conductance fluctuation arises from the mobile defects whose rotation and change in separation modify the resistivity tensor. The theory gives an expression for the relative fluctuation $\langle \delta G^2 \rangle / G^2$ in terms of measurable or calculable parameters. In this model, the temperature dependence arises from the thermal activation of mobile defects, which cause the conductivity fluctuations. The LI noise is expected to dominate at higher temperature where the UCF is not operative because the mean free path $l_{\mathrm{e}} > L_{\varphi}$.

$$N\left[\frac{\langle (\delta G)^2 \rangle}{\langle G^2 \rangle}\right] = \left(\frac{n_{\mathrm{m}}}{n_{\mathrm{A}}}\right) (n_{\mathrm{A}} l_{\mathrm{e}} \beta_{\mathrm{c}} \sigma_{\mathrm{c}})^2 \tag{14}$$

where N is the total number of conduction electrons in the volume of the sample, n_A = atomic density, n_m = concentration of mobile defects that contribute to local interference in the time scale of the noise measurement, l_e = electron mean free path, β_c = anisotropy constant for the resistivity tensor and σ_c is the average scattering cross-section. It can be seen that the anisotropy factor is very important in this model because absence of an anisotropy factor in the resistivity tensor will give rise to no noise.

The origin of $1/f$ noise in the models based on smeared activated kinetics is superposition of fluctuations from independent fluctuators whose individual contribution is a Lorentzian given by Eq. (4). A very clear experimental demonstration is seen in development of the power spectrum $S(f)$ in MOS devices and small junctions. In small devices the conductivity fluctuation which shows Random Telegraphic Noise (RTN) has an $S(f)$ given by Eq. (4). As the size increases, one sees development of a $1/f$-type power law spectrum [*24].

5. Experimental determination of noise

The quantity observed experimentally is the fluctuating physical quantity (say a voltage $v(t)$) as a function of time around a mean defined as $\delta v(t) \equiv v(t) - \langle v \rangle$, where $\langle v \rangle$ is the average. The main information is contained in this time series $\delta v(t)$. Often the information can be obtained from the distribution of voltage jumps $P(\delta v(t))$ or the mean square fluctuation within a given bandwidth, $\langle (\delta v(t))^2 \rangle$. However, the most popular way to represent the noise is through the power spectrum $S(f)$. The frequency range for which the spectral power is to be determined depends on the time scale of the fluctuations being investigated. In general, if the dynamics are occurring at a time scale τ, it will affect the power spectrum around the frequency range $f \sim (1/2\pi\tau)$. It is also important to ensure that the noise originates from the sample since many of the associated measuring electronics also have $1/f$ noise.

A common way to measure $1/f$ noise is to bias the sample with a dc. In general, a four-probe configuration is used where the biasing current is applied through two separate leads just like in a four-probe resistivity measurement. The biasing current being dc, the steady voltage drop across the sample is blocked off by a capacitor bank forming a high pass filter. The fluctuating voltage across the materials to be studied is then amplified by a low-noise preamplifier (for samples with relatively higher resistance) or a low noise transformer for more metallic samples. The power spectrum can be obtained using a commercial spectrum analyser or the time series, $\delta v(t)$, can be digitized and the power spectrum be obtained from the FFT of the correlation function of the time series. The ease of use has made the spectrum analyser the most common method. However, in this method one loses all the information on the time series like the $P(\delta v(t))$. Since the $1/f$ noise is generally measured well below 10 KHz, digitizing the time series and using a separate FFT programme is a better alternative. This is because, the digitized time series $\delta v(t)$ is stored in the computer and one can carry out all the algebra with it leading to a more complete analysis of the data. With availability of relatively high speed (>200 KHz) A/D cards (more than 16 bits) and the decreasing cost of computers, this is definitely a preferred option. In order to separate out the $S(f)$ due to background the data are taken with zero bias current and then $S(f)$ is measured with a finite dc bias. The difference gives the noise due to the system under measurement.

The four-probe dc method suffers from two very important drawbacks: (a) the $1/f$ noise of the preamplifier and the associated electronics adds to the background and raises the noise floor of the measurements; and (b) the background estimation can be very faulty because it can shift during the measurement itself since long data collection times are necessary at lower frequency. If one uses an ac technique, both the drawbacks can be removed.

In the ac technique, the sample is biased by an ac and the signal is demodulated by a lock-in amplifier. This shifts the detection frequency to a region where the preamplifier has very low $1/f$ component. The signal from the lock-in is then digitized where the bandwidth of the low-pass filter of the lock-in amplifier will dictate the maximum frequency of the spectrum. In this case the carrier frequency $\gg$ bandwidth of measurement. For measuring spectra with $f < 10^2$ Hz this is a convenient technique. In addition, if the signal is recorded at two phases, it can be shown that the in-phase part will give a power spectrum that is a sum of both background and 'signal' while the out-of-phase component gives the background only. The power spectrum of the noise from the sample ('signal') can be obtained by subtracting the background, which is measured simultaneously. This simultaneous measurement of the background is the greatest advantage of the ac technique. A much-improved version of the ac technique is the five-probe technique where the middle electrode is grounded. The sample forms two arms of bridge, which can be balanced by low noise wire-wound resistors in the other two arms. Balancing the bridge can raise the sensitivity many folds and the contributions to noise by temperature drift etc. are largely cancelled out [*25,26,27]. The five-probe ac technique has higher sensitivity.

The methods to be used for noise measurements depend on the extent of noise which one would like to measure. When the spectral power of the sample noise is $>10^{-15}$ V^2/Hz, the background is often not a problem and the simple dc method will suffice. However, noise measurements in relatively clean systems and metallic systems can involve spectral power as low as 10^{-20} V^2/Hz or even lower. In that case the measurement requires special care and the background noise subtraction is a very important

issue. The five-probe ac method is the best solution for low noise measurements.

Noise measurements often suffer from the problem of irreproducibility, particularly in the absolute magnitude. There are two principal causes for this: (a) improper background subtraction and (b) contact noise. If the background is uncertain (as it often happens in a four-probe dc method), then its subtraction may not be accurate enough, leading to irreproducibility of results. In an ideal case the background should be close to the thermal background of $4k_BTR$ if the measurements are carried out in a shielded enclosure. In order to ensure that the background is reproducible it is good practice to check that the measured background noise is close to the expected thermal noise. The contact noise is another source of irreproducibility of noise measurements. Even in a four- or five-probe geometry one can get contributions from the contact noise which can itself have $1/f$-type spectral power. An ohmic contact or an observed quadratic dependence of $S(f)$ on the bias is no guarantee that the contact noise is negligible. The absence of contact noise contributions can be tested by making measurements with contact areas of different sizes and also by making measurements with different sample volumes (Ω). The measured $S(f)$ should follow the relation $S(f) \propto 1/\Omega$. An inverse volume dependence of the observed noise is the best indication that the measured noise is originating from the bulk of the solid.

Recently the field of noise spectroscopy has been innovatively coupled to other measurement techniques. This makes the noise technique more powerful and adds a new dimension to the experiment. A recent method to measure noise with a pulsing dc superimposed on ac has been proposed to obtain information on the spatial correlation of the inhomogeneous current path in percolating system [28]. A recent experiment involving noise spectroscopy in an EPR cavity shows how the electronic centres involved in the resonance contribute to the GR noise [29].

6. Noise in metallic systems

Metallic thin films are one of the most studied systems and these measurements have contributed significantly to the development of some of the most basic theories of noise. These experiments have established that in metallic films the noise has a defect origin [**2,*11,*30] and the power spectrum reflects the dynamics of defect relaxation. It is a common observation that films of good quality have less noise. A typical metal film generally has $\gamma_H \leq 5 \times 10^{-3}$. Although the exact nature of the defects may not be known, in most cases the DH model provides a correct description of the power spectra implying that the defect relaxation follows activated kinetics. (An alternate approach to obtain smeared activated kinetics is through a distribution of prefactors τ_0 in the relation $\tau \equiv \tau_0 \, e^{E/kT}$ and not a distribution of $D(E)$ of E as in the DH model. Experimentally it is difficult to distinguish between these models [*30].

If the defect relaxation is activated the temperature dependence of the spectral power also should show activated behaviour because as the temperature increases more defects become mobile in the time scale of noise measurements. Due to this aspect, temperature dependence of the noise can be a very nice way to measure activation energy of defect motion in solids [31]. It should be mentioned that the temperature dependence of $S(f)$ in metals might not always show a clear activated temperature dependence [*32]. Under what conditions this happens has not been ascertained yet. At temperatures $T < 100$ K, in disordered metal films, $S(f)$ rises again as T is decreased following a temperature dependence $T^{-1/2}$ [33]. This rise is due to UCF. In Fig. 3 we have shown a compilation of the temperature dependence of noise seen in metallic Ag. The noise has an activated T dependence at high T. The rise in noise at low T is due to the UCF mechanism [33].

However, to gain more definitive information from noise spectroscopy, it is important to know the nature of the defects that contribute to noise and the coupling mechanisms that produce fluctuation in conductivity due to the defects. A very important class of experiments has been carried out on Pd and Nb films, which are loaded with H [*30,34]. These are some of the limited experiments where a clear connection can be established with the defect that creates noise. In these materials the diffusion of hydrogen in the material at higher temperature and localized hopping

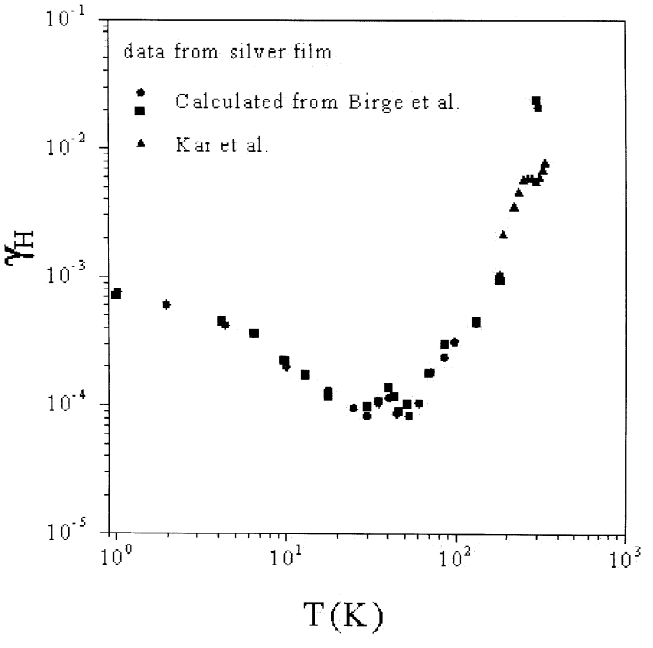

Fig. 3. Temperature dependence of the noise in a metallic film (Ag) from 2 to 500 K. The data shows the low temperature UCF dominated region and the high temperature activated region. Data compiled from Refs. [33,47].

of hydrogen from site to sites at lower temperatures have been identified as the source of low frequency fluctuations. It is the local density fluctuation of H that has been suggested as the cause of local resistance fluctuation. An interesting scaling law has been found for noise arising from the diffusing species [*30]:

$$\omega S(f)/\langle \delta\rho^2 \rangle = P(\theta)$$
$$\theta(\omega, T) \equiv \frac{\omega}{D(T)} \quad (14)$$

The scaled frequency $\theta(\omega, T)$ is defined through the actual frequency $\omega(\equiv 2\pi f)$ scaled by the diffusion constant $D(T)$ which has a temperature dependence $D(T) = D_0\ \mathrm{e}^{-E/kT}$, E being the activation energy of diffusion. $P(\theta)$ is a function of the scaled variable θ. Recent computer simulations specifically address the issue of light interstitial impurities on $1/f$ noise [35]. It was found that the noise magnitude increases with clustering of defects and the shape of the activation energy distribution function provides information on the nature of defect ordering.

While point defects like hydrogen in metals (which give rise to Snoek relaxation) can contribute to resistivity fluctuations, it appears that thermally activated motion of extended defects like vacancy clusters, clusters of dopants (substitutional and interstitials) and dislocations are stronger candidates for producing resistivity fluctuations. In polycrystalline metal films, for example, most of the noise arises from the grain boundary.

A very interesting application of current noise to study formation and relaxation of dislocations during plastic deformation has been demonstrated in aluminium films [36]. Noise has a strong correlation with the dislocation generation and annihilation process and a quantitative estimation of the dislocation density from the observed noise magnitude can be obtained. A recent experiment on Al films of well-characterized microstructure has shown that the noise in monocrystalline lines arises due to thermal motion of atoms along dislocation [37]. While in polycrystalline lines the thermally activated motion of defects in the grain boundaries is the principal source of noise.

In addition to temperature, stress is an important variable that plays a key role in defect ordering and the resulting dynamics. Although there are not many studies of stress effect on noise, from the available experiments it appears that more investigation could make this a very useful tool in materials science. The application of stress was found to significantly affect the noise (which retains its $1/f$ spectral power) in Au and Pt films [38]. As the stress relaxed slowly over time, the noise also relaxed. The experiment reached the important conclusion that whatever be the mechanism that produces $1/f$ noise in metal films; it is sensitive to the strain. This also suggested that the built-in strain in the films can be the cause of widely differing noise magnitude found in nominally similar metal films. In recent experiments on stainless steel wires interesting stress induced effects have been found. In addition to broad $1/f$ noise the stress induces narrow band noise, where the frequency depends strongly on the applied stress (σ). The noise $\langle \delta v^2 \rangle$ was found to follow a scaling function with the ratio (σ/T) [39].

Simultaneous measurements of anelastic piezo-resistance and noise were done in H containing Bi, Nb and Fe films [40]. In this experiment, the attempt was to find the Snoek relaxation of H defects through anelastic piezo-resistance measured and to correlate the anelastic relaxation with noise, which is expected to arise from the same source of defects. While a strong correlation was found for Bi film, no correlation was found from Fe film and a partial correlation of the two was found in Nb film. It was concluded that the difference arises in the difference of the coupling of the defects, which produce resistivity fluctuations and those couple to the strain field. There is a need to perform such classes of experiment to understand the full impact of strain, and strain inhomogeneties on $1/f$ noise. Given the sensitivity of the noise to strain it is quite likely that this can be effectively developed as a tool of strain characterisation in metal films.

In polycrystalline metal films the most prominent source of noise is the grain boundary (GB). The GB provides the weakest link in a film and is the path along which atomic migration can take place by GB diffusion or by more complicated defect complexes. The activation energy of such GB diffusion being low, it can act as a source of low frequency fluctuation that can contribute to $1/f$ noise. $1/f$ noise has been measured in sub micron size metal films with and without GB (single crystal) [41]. It was found that in single crystalline gold films (without GB), the noise is about $1/3$ of that in films with GB. This conforms with the earlier experiments on Al based interconnects [31]. Subsequent experiments have established a close link between $1/f$ noise and the microstructure and texture [*42]. The magnitude of the $1/f$ noise also has an interesting dependence on the grain size in films [43]. The noise was found to be a function of the ratio (a/d), where a is the average grain diameter and d is the film thickness. For $a/d > 0.5$ $\gamma_H \propto 1/a$. However, for smaller grains (granular films) γ_H is a strong function of (a/d).

Use of $1/f$ noise to predict electromigration (em) induced failure of metal films and interconnects is a topic of considerable interest from the viewpoint of reliability of VLSI circuits [44,45]. The grain boundary diffusion is identified as the principal source of em failure in metal films. Since noise in metal film is also directly linked to atomic motion in the GB, it is expected that the two will have a relation. In the past decade well-controlled experiments have established a correlation between the mean-time-to-failure (MTF) and the noise quantified by γ_H. It was found that films with a higher MTF have a lower γ_H. Fig. 4 shows two important sets of results. In Fig. 4(a) we show how at the onset of the electromigration the noise rises by a large factor [*46], and it rises in steps. Fig. 4(b)

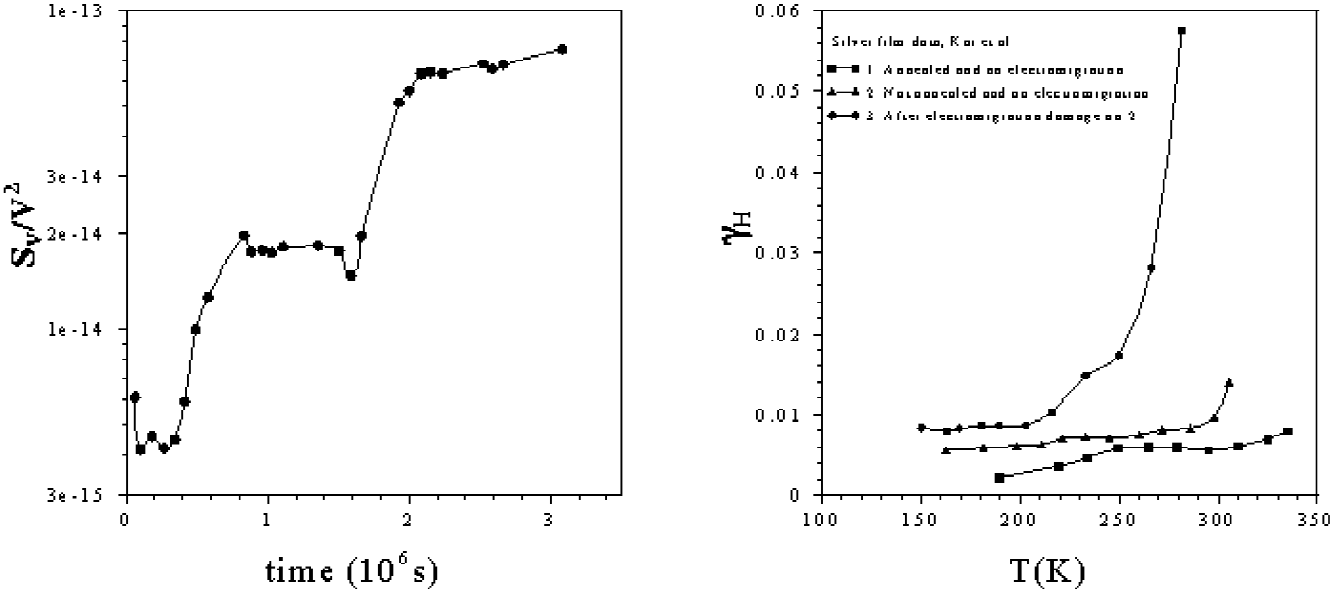

Fig. 4. (a) Increase of noise at the onset of electromigration in Al interconnects (data compiled from Ref. [*46]). Note the step-like increase of the noise. (b) The increase in the noise as a function of temperature in Ag films after prolonged current stressing (data compiled from Ref. [47]). Note the strong temperature dependence of the noise in the film with em current stressing.

shows that in metal films with and without em damage, the temperature dependence of noise is significantly different. In the film with em damage the noise rises rapidly at higher temperatures [47]. In both the cases the changes in resistance of the film are too small to be detected compared to those seen in the noise. In addition to these important observations, the other significant observations made by different experimenters in this field of investigation can be summarized as follows:

1. Films with lower γ_H have higher activation energy as seen in the temperature dependent MTF experiments.
2. The noise is significantly higher when the em failure sets in.
3. The noise shows a perceptible increase at the onset of em even before noticeable changes can be seen in resistance which is often used to monitor em failure.

It is expected that over the coming years more well controlled experiments will be done so that the noise technique is established as a viable tool for failure prediction of metallizations and interconnects. In addition to noise experiments on films with electromigration damage, it is necessary to do well defined experiments on metal films after stress stretching. There are also reports of on-chip noise measurements [45].

7. Noise in semiconductors

Noise in bulk or epitaxially grown semiconductors as well as in semiconductor devices have been investigated extensively over the years. These investigations have been motivated principally from the viewpoint of understanding the noise in semiconductor devices so that they can be controlled. The noise in devices, in particularly at low *f*, has a significant component arising from the device material itself. As a result the study of noise in semiconductors is an important field or research. This is becoming more important as the device size is being reduced. Due to limited scope this review would discuss the investigation of noise in semiconductors only and readers are referred to other publications for the area of devices [48].

Noise has been extensively investigated in the two widely used device materials Si [49–53,*54] and GaAs [55–61,*62,63–65]. Most of the studies are done at or around room temperatures (300 K). Some of the studies have been extended down to liquid nitrogen temperature. In very recent times there have been reports of noise investigation in heavily doped Si down to 2 K [66,*67,68]. Understandably, in semiconductors noise investigations down to liquid He temperature or below can only be done in heavily doped semiconductors whose resistance does not blow up on cooling. There have been reports of investigations of noise on the wide band semiconductors GaN [69–72] and to a limited extent on SiC [73]. In addition, $1/f$ noise has also been studied in other materials like InP [74] and HgCdTe [75]. In early years the materials studied were often bulk crystals. However, in recent years noise has been investigated in epilayers of different semiconductors grown by physical vapour transport mechanisms like molecular beam epitaxy (MBE) or chemical vapour transport deposition like metallo–organic chemical

vapour deposition MOCVD. This brings the investigation closer to actual application and makes it more relevant to devices. Most notable are the investigations in very high mobility GaAs or AlGaAs epilayers that form the core of optoelectronics or microwave frequency devices. There have also been studies on polysilicon resistors of Si and SiGe [76]. Ion implantation by energetic ions (>100 keV) has been used in some investigations as a method to create defects which can be annealed on heating [50,52,60]. These studies allowed investigations of the effect of lattice disorder on the noise. Since ion implantation is widely used for semiconductor device processing, this is a valuable investigation. It can be seen from the range of studies, as well as the focus on certain types of materials, that the principal motivation of these investigations is to contribute to our understanding of noise in solid state devices. However, heavily doped semiconductors may turn out to be model systems for investigating fundamental aspects of $1/f$ noise [77].

The study of noise in semiconductors requires caution for two important reasons. Firstly, if the contact is non-ohmic and of high resistance, it can be the source of noise. Secondly, in many semiconductors the source of noise may not be the bulk, but the surface or interfaces. In devices, in particular, interface states can be the predominant source of noise. As pointed out before, an experiment as to whether the spectral noise $S(f)$ displays an inverse dependence on volume will help to identify whether the noise arises from the bulk.

From the multitude of studies done on semiconductors over the last decade or so the following observations can be made:

1. The magnitude of noise (at room temperature) as expressed through γ_H can have widely different values ranging from as low as 10^{-6} in some epitaxial layers to 10^{2} in some samples. This clearly indicates that the noise depends on the purity and quality of the sample and depends particularly on structural defects that are present. However, a quantitative and rigorous correlation between the density and nature of defects to the noise observed has rarely been done.
2. The noise can arise in the bulk as well as at interfaces, and the spectral power $S(f)$ can have a $1/f^{\alpha}$ ($\alpha \sim 1$) component and a component that can be resolved into distinct Lorenztians. In investigations which have been carried out over a reasonable temperature and frequency range, the $S(f)$, in general, can be expressed as:

$$S(f,T) = \frac{A(T)}{f^{\alpha}} + \sum_{i=1}^{n} B_i(T)\frac{2\tau_i}{1+(2\pi f\tau_i)^2} \qquad (14)$$

where, A is a frequency independent but temperature dependent constant that measures the strength of the $1/f$ type contribution and B measures the strengths of the individual Lorentzians with characteristic corner frequency τ^{-1}. Since the discrete Lorentzians in most cases originate from GR mechanism, we will refer to them as GR type noise.

3. The noise increases in most cases as the temperature increases ($T > 150$–200 K). However, since in many cases the temperature range studied is limited, a definite functional relationship of $S(f)$ with T cannot be established. There is clear evidence, wherever the measurement has been carried down to reasonably low temperature, that $S(f)$ increases on cooling below 100 K.
4. There is a consensus that the discrete Lorentzians arise from the generation-recombination mechanism from traps within the gap and in many cases, these traps can be deep levels.
5. The origin of the $1/f$-type term is still a point of debate. In general, three models are generally proposed to explain the occurrence of this term near the room temperature. These are the lattice model [*8], the LI model [*17] and the model due to trap states near the valence or conduction band [19].

In the following, we give examples to elucidate some of the observations made. In Si with low doping concentration, the γ_H lies in the range 10^{-7}–10^{-2} at room temperature, with the exact value being a sensitive function of impurity and defect process conditions. One of the early studies of epitaxial n-Si (on Sapphire) with carrier concentration 5×10^{16} cm^{-3} showed a rather low γ_H, but the source of noise could not be located (bulk or surface). The noise studied in the range $77<T<300$ K has a temperature dependence with a shallow minima around 200 K [49]. The link between the noise and the defects was established in Si through ion implantation studies [50,52,53]. Crystalline n-Si (P, carrier concentration $\approx10^{15}$ cm^{-3} with a mobility $\mu\approx270$–300 cm^2/V/s and an $\gamma_H\approx 10^{-7}$–10^{-6}) was implanted with B with energies upto 1 Mev. On implantation, the sheet resistance as well as γ_H increased and on subsequent annealing at different temperatures (T_{an}) recovered and showed a significant reduction in noise. The noise had both a $1/f$ as well as a GR type discrete Lorentzian contribution. γ_H increases, as the temperature is increased upto room temperature. An interesting observation was that while the sheet resistance reduced on annealing by a factor of three or four, the γ_H reduced by three to four orders on annealing, following an activated behaviour with annealing temperature ($\gamma_H \propto \exp(E_{an}/T_{an})$) with activation energy $E_{an}\approx1$ eV. This particular observation established a close link between noise and the defects created by the irradiation process. Subsequent experiments were carried out on n-type Si grown by float-zone technique with low doping density (2×10^{13} cm^{-3}) and very high mobility ($\approx1.2\times10^{3}$ cm^2/V/s) samples. These samples displayed $\gamma_H\approx3\times10^{-4}$ at room temperature and the noise had both $1/f$-type and GR components [*54].

$1/f$ noise has been investigated on crystalline Si heavily

doped (with P and B) with charge carrier concentration $n \geq n_c$, where n_c is the critical concentration for an insulator–metal transition (Anderson Transition) [6,66,*67,68]. Studies were done with both *n* type (*P* doped) and *B* compensated crystals. The high carrier concentration and low mobility ($\approx$50–100 cm^2/V/s) gives a rather high noise ($\gamma_H \approx 0.1$–1) at room temperature, particularly when $n \approx n_c$. The noise has a pure $1/f$-type component for samples which have $n > n_c$ but shows GR type contribution in the samples in the insulating side in the temperature range $200 < T < 500$ K which have well defined activation energies. In these heavily doped materials the noise was measured over an extensive temperature range $2 < T < 500$ K. The temperature dependence is shown in Fig. 5. The conductance fluctuation shows a minimum at around $T \approx 150$ to 200 K range. It shows an activated temperature dependence at high temperature with the activation energy ≈ 1 eV for the most metallic samples, decreasing in samples with lower carrier density. The data in this region can be explained by a combination of the DH and LI models. At lower temperatures, a region that has been investigated rigorously, the noise rises again with temperature dependence T^{-1} [*67,68]. Suppression of noise by a magnetic field shows that the noise at low temperature arises from UCF. The similarity of the temperature dependence of noise in Ag (see Fig. 3) and in heavily doped Si is striking. In this range, the heavily doped Si is like a disordered 'metal'. In Fig. 5, we have also plotted a collection of the data on the temperature dependence of γ_H in a number of Si samples with much lower doping. These data have been compiled from Ref. [51]. There is a general trend of γ_H decreasing with temperature down to 80 K. The data also clearly shows the sensitivity of the noise to various annealing treatments.

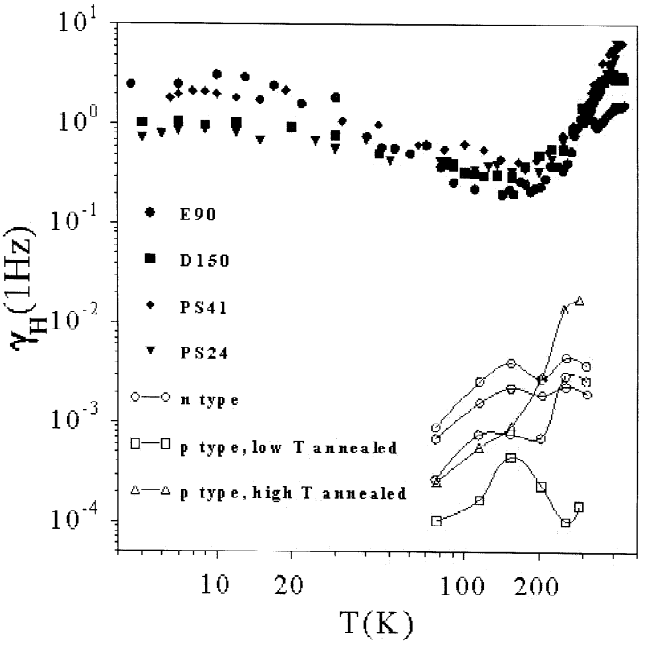

Fig. 5. Temperature dependence of the noise (expressed as γ_H) from $2 < T < 500$ K in Si with different levels of doping (*P* and *B*). Data on low doping are from Ref. [51]. The data on heavily doped Si are from Refs. [6,66,*67].

Most of the experiments on GaAs were carried out on epilayers. It had been established that noise spectroscopy (particularly the GR noise) could be linked to defects, like DX-centres, in GaAs/$Al_xGa_{1-x}As$ heterostructures [56]. A very early study on high mobility ($\mu \approx 7 \times 10^3$ cm^2/V/s) epitaxial *n*-type (Si doped, 10^{15} cm^{-3}) GaAs showed that damage induced by uniaxial compression can change the γ_H by large amounts while μ is reduced only by a factor of three [12]. This established the sensitivity of $1/f$ noise to lattice imperfections. Noise in Si doped *n*-type GaAs epilayers was studied with carrier concentrations in the range 0.4×10^{15} to 0.7×10^{17}cm^{-3} over the temperature range 80 to 300 K [57,58]. The materials with a high mobility (≈ 5–10×10^3 cm^2/V/s) show a $\gamma_H \approx 10^{-4}$–10^{-3} and a temperature dependent $1/f$ noise which shows an activated temperature dependence for $T > 150$ K, with activation energy in the range 0.15–0.20 eV. The activation energy increases as the carrier concentration and doping level increases. Recent experiments [59,61,*62,63–65] on epitaxial GaAs use heterostructure with $Al_xGa_{1-x}As$ (typically $x \approx 0.3$) to confine the charge transport and doping was done using δ-doped Si. The noise had both $1/f$ and GR type components (for $T > 150$ K) which can be changed on illumination. The GR noise was related to deep levels and such centres as DX centres. It appears that noise spectroscopy can be used as viable tool to study defect relaxation in GaAs based heterostructure devices.

The increasing application of wide band gap GaN in optoelectronics has shifted considerable attention to GaN. In GaN a relation of the quality of the material and γ_H has also been established. In *n*-type GaN (doping level 10^{18} cm^{-3}), as μ increases from 60 to 790 cm^2/V/s, γ_H decreases from nearly 3 to 0.05 [69,71]. Mg doped GaN (p-type) has low μ ($\approx$10 cm^2/V/s) and the observed γ_H is very high $\approx$1–150 [72]. An interesting correlation of the line width of the X-ray rocking curve with noise has been established. The noise has both $1/f$ and GR type contributions which arise from trap levels lying within 0.1 eV of the valence band. It is expected that in the coming years there will be more noise spectroscopy studies of GaN.

Amorphous semiconductors have also been studied using noise spectroscopy. *a*:Si seems to be the most studied material in this category although there are interesting noise studies on *a*:SiC [78,79] and *a*:C [80]. *a*:SiC (hydrogenated or non-hydrogenated) show both $1/f$ noise and GR type noise like other semiconductors. *a*:SiC prepared by RF-sputtering shows both $1/f$ and GR noise in the as-prepared sample. On annealing, the GR part is removed. In comparison, glow discharge prepared *a*:SiC shows only $1/f$ noise. This is yet another example of sensitivity of noise to processing parameters.

a:Si (H) is the most studied amorphous semiconductor

using noise spectroscopy [28,81,82,*83,84,85]. In addition to technological demand of *a*:Si (H) as device material, noise in this material shows features often not shown in homogeneous crystalline semiconductors. The conductance fluctuation shows a $1/f$ component interspersed by RTN. The spectral power itself shows noise and is strongly non-Gaussian, which implies a spatial correlation between fluctuating regions. It appears that diffusing hydrogen is the source of noise in this material. From experimental investigation, modelling and simulation it appears that the current flow in this material is inhomogeneous in nature and takes place through a filamentary route which arises from a percolating path. The conduction in the filaments is modulated by the diffusing H. It is proposed that the diffusing H introduces changes in Si–Si strain field, which being a long range potential can introduce correlation within filaments or among the filaments. The correlation of the fluctuation also suggest the existence of a serial (hierarchical) relaxation process in contrast to the parallel independent relaxation of fluctuators seen in most other materials. Recently the GR part of the noise was found to be affected when the noise was measured under the condition of spin resonance thus linking this noise to spin dependent defects [29]. The investigation of noise in *a*:Si (H) clearly showed the power of analysing the non-Gaussian noise spectra and also how the noise measurement can be made more useful by coupling with other techniques. Investigation on *a*:Si (H) is not only important for the investigation of the material itself, it can be a useful model of a class of inhomogeneous and non-linear materials.

8. Noise in metallic oxides

Metallic oxides are increasingly playing an important role in electronic devices. The metallic oxides of perovskite structure like $LaNiO_3$, $SrRuO_3$ and $La_{0.5}Sr_{0.5}CoO_3$ are important interconnect and electrode materials in oxide electronics. In addition to the normal metallic oxides, two other families of metallic oxides have contributed much to the recent excitement in this field. They are the cuprates, which show high temperature superconductivity and the rare-earth manganites showing charge ordering (CO) and colossal magnetoresistance (CMR). A very important endeavour in this field is to grow high quality films for device applications as well as for investigation of basic physical properties. The noise in these materials can be used to assess the quality of the films. As an example, in the high T_c superconducting (HTS) cuprates (like $YBa_2Cu_3O_7$) the γ_H was in excess of 10^9 when these films were first made [86]. However, in recent years γ_H has come down to close to 2×10^{-6} as reported in an epitaxial film of $YBa_2Cu_3O_7$ grown on $SrTiO_3$(STO) substrate by laser ablation [87]. The film has a low dislocation density of about $10/\mu m^2$. In the case of CMR films there are reports of γ_H as low as 8×10^{-2} for epitaxial LCMO films grown on a lattice matched NGO ($NdGaO_3$) substrate [*88]. An interesting investigation showed how high-energy heavy ion implantation (250 MeV ^{107}Ag) leads to enhancement of the noise in these materials, much like those found in irradiated metals and semiconductors and confirming the defect origin of the $1/f$ noise [89]. The nature of defects created by high energy heavy ions in oxides is different from those created in metals or semiconductors. Using noise spectroscopy to study the nature of radiation induced defect in metallic oxides is a useful endeavour. In addition to quality control of films, noise can be used as a probe of some fundamental physical process in these materials (like flux noise in HTS below T_c [*90] and electronic phase separation in manganites [91]. There are certain generic issues concerning noise in all these metallic oxide materials. We summarize them below:

1. The most likely source of noise in these materials is associated with motion of oxygen. This is because in most of the perovskite oxides, oxygen is a particularly mobile species and has a much smaller activation energy of migration (often <1 eV). This is much less than that of the cations. Also the perovskites are defect stabilized and contain oxygen vacancies that facilitate oxygen migration. Interestingly oxides like the rare-earth manganites (CMR oxides) are used as oxygen conductors.
2. The electronic charge transport is strongly related to the presence or absence of oxygen at a lattice site. This is because an oxygen-transition metal–oxygen network (2D or 3D) determines the conduction path. As a result, a small fluctuation associated with local oxygen density can cause appreciable conductance fluctuation.
3. The noise is a strong function of oxygen stoichiometry but is not a monotonous function. In some cases, the noise shows a low value at certain non-stoichiometric conditions.
4. These materials are susceptible to strain which plays a very important role in deciding the charge transport. As a result, the presence of inhomogeneous strain can cause a large conductance fluctuation. It is to be noted that the strain in the grown layer (arising due to substrate quality, growth condition, lattice mismatch and the thickness) can be large and inhomogeneous. Therefore, the noise in these films are large and are often irreproducible even if the resistances are reproducible. Good control of the film growth, control of strain and oxygen stoichiometry are necessary to produce low noise oxide films
5. Devices made from artificial grain boundaries are common in these oxides. GB (particularly high angle GB) is a prominent source of noise.
6. The oxide interconnects are susceptible to electromigration of oxygen ions. This is a serious cause of lack of stability. In oxides since noise can be linked to oxygen migration, it provides a good probe of this process.

In the case of the oxides, the close link between oxygen migration and $1/f$ noise has been clearly established in epitaxial films of $YBa2Cu_3O_7$ (Cu-123) [92,93] and $LaNiO_3$ (LNO) [94,*95]. In the case of LNO the noise and electromigration was studied in detail. A quantitative link between the two was established by comparing the noise spectra (measured over a substantial f and T range) with that calculated from the experimentally measured relaxation function $\varphi(t)$. $\varphi(t)$ can be obtained by measuring the time dependent resistance change due to electromigration which follows a stretched exponential. In Fig. 6, we show an example of a typical stretched exponential fit to the resistance vs. time curve in LNO at different temperatures obtained in the electromigration experiment. The relaxation function $\varphi(t)$ (of the form $\sim\exp[-(t/\tau)^{\beta}]$) was obtained from a fit to the data and the $1/f$ noise was measured in the same sample at 315 K. The measured noise (points) were found to match the calculated spectral dependence (solid line) over a substantial frequency interval [*95]. $S(f)$ was calculated from the experimental $\varphi(t)$ using Eq. (3). The relaxation time τ follows Arrhenius temperature dependence, as shown in the inset of Fig. 6.

Although it is known that the noise in an oxide film is a strong function of the oxygen stoichiometry, there are not too many experiments that have performed a quantitative correlation. From the available experimental data, where noise was measured as a function of the oxygen stoichiometry, it was found that the noise can have a non-monotonous dependence on the oxygen stoichiometry. It sometimes reaches a minimum at an oxygen stoichiometry, which may not correspond to the most oxygenated metallic sample. This is shown in Fig. 7 for $YBa_2Cu_3O_{7-\delta}$ [96] and $LaNiO_{3-\delta}$ epitaxial films [94]. It can be seen that the room temperature noise in LNO reaches a minimum at $\delta\approx 0.025$ and in Cu-123 the minimum is at $\delta\approx 0.5$. The origin of such behaviour is not yet known.

The $1/f$ noise in the Cu-123 system has a strong dependence on the substrate [*90] as well as on the growth direction [97] and the presence of grain boundaries [98]. An interesting example of the dependence of noise on the direction of growth has been seen in Cu-123 grown on STO [97]. It was found that the c-axis oriented film had much less noise.

Rare-earth manganites (with mixed valent Mn in Mn^{3+} and Mn^{4+} states) that show CMR and CO have attracted a good deal of current attention. Noise has been investigated rather extensively in these materials [*88]. In Fig. 8 we give a compilation of the temperature dependence of the spectral noise in two of these materials, namely LCMO [89,*99,100] and LSMO [101] prepared on different substrates. These data can be taken as examples of the observed noise in these films. One of the experiments is on a single crystal of LSMO of rather low resistivity [102]. Data presented are spectral densities ($=fS(f)/V^2$). (They have not been scaled by sample volume and carrier density to get γ_H). It is apparent that there is a strong dependence of the observed noise data on various growth parameters. For instance, both the LCMO films shown in Fig. 8, were grown on $LaAlO_3$ substrates using laser ablation although of different thickness and presumably of different oxygen stoichiometry. One of the films [100] with larger thickness (0.4 μm) has lower T_c and higher resistivity compared to the other film [89]. It shows a peak in noise at $T/T_c\approx 0.36$ while the other film shows a shallow peak close to $T/T_c\approx$ 0.78, Such a peak has also been seen in the noise in LCMO films grown on STO [*88,*99] although the temperature at which the maximum occurs can vary widely. Such a feature is completely absent in LCMO

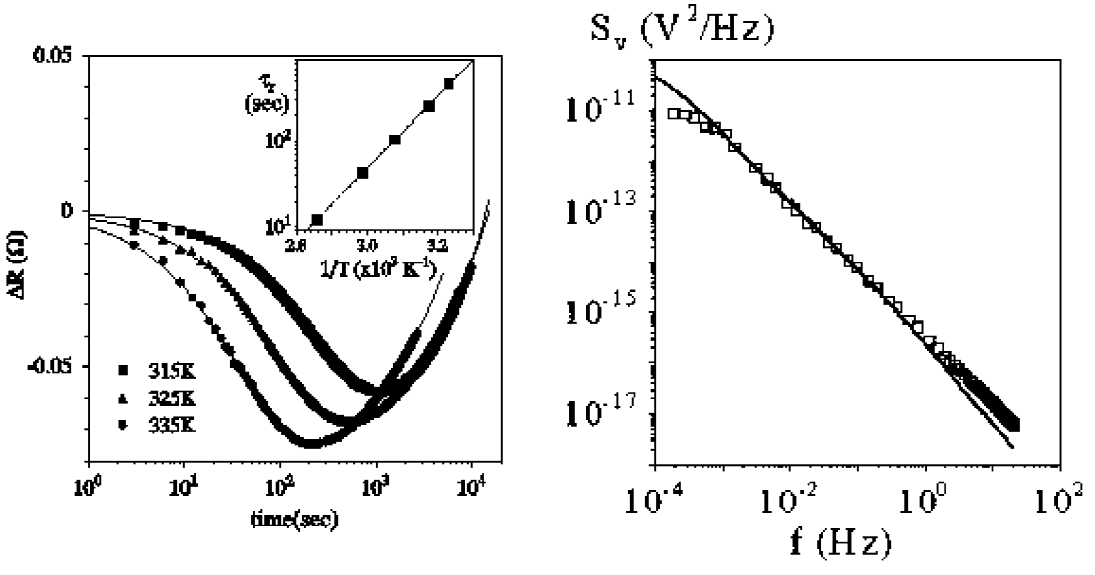

Fig. 6. (a) Stretched exponential resistance change in epitaxial films of $LaNiO_3$ on application of dc stressing current. The time dependence of the resistance can be used to find the relaxation function. (b) A comparison of the calculated spectral power of noise (lines) with that obtained from the experiment. (Data from Ref. [*95]).

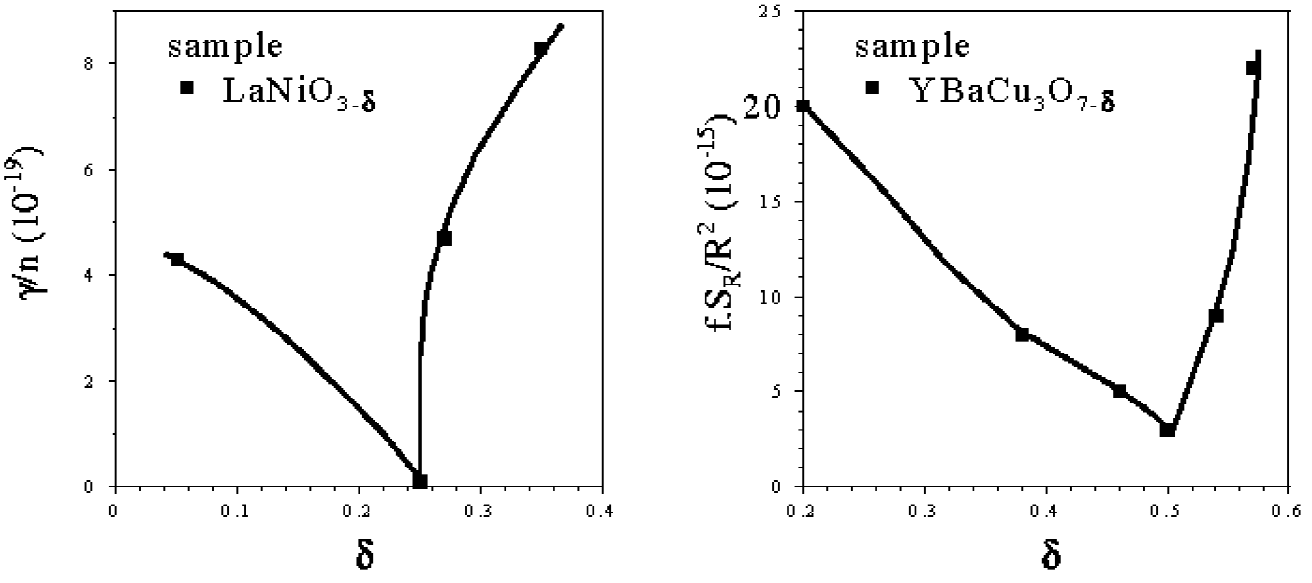

Fig. 7. Dependence of the room temperature noise in two oxide films. The data on LNO (noise expressed as γ_H/n where n is the carrier concentration) are complied from Ref. [94]. For the $YBa_2Cu_3O_7$ system the noise is minimum at $\delta \approx 0.5$ (Ref. [92]).

grown on NGO which has a better lattice match and gives a low noise film [*88]. The data shown in Fig. 8 was taken on LSMO films grown on MgO substrate [101], the temperature dependence of the noise in the film is qualitatively different from that observed on the LSMO single crystal [102]. It is clear that the observed noise in CMR systems is a strong function of the quality of material and there is a need to characterize the samples before the noise data are taken.

One motivation of using the noise probe is to investigate the phenomenon of electronic phase separation that leads to coexisting phases of similar energy but of different conductivity [91]. These two phases are separated by an energy barrier that determines the dynamic transition

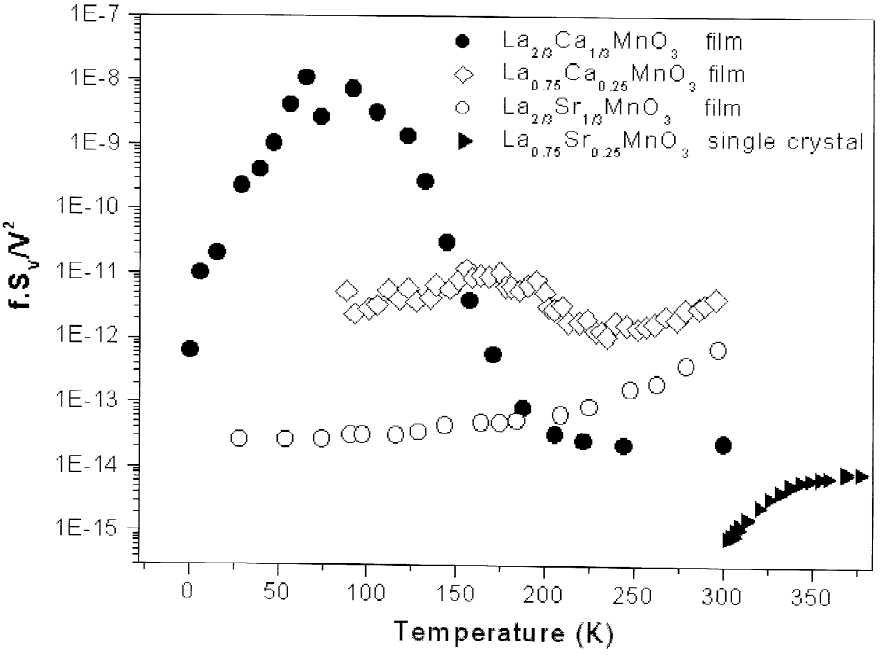

Fig. 8. Dependence of scaled noise on temperatures in CMR materials. Data on LCMO films are from Refs. [89,100]. Data on LSMO film are from Ref. [101] while that on LSMO single crystal is from Ref. [102].

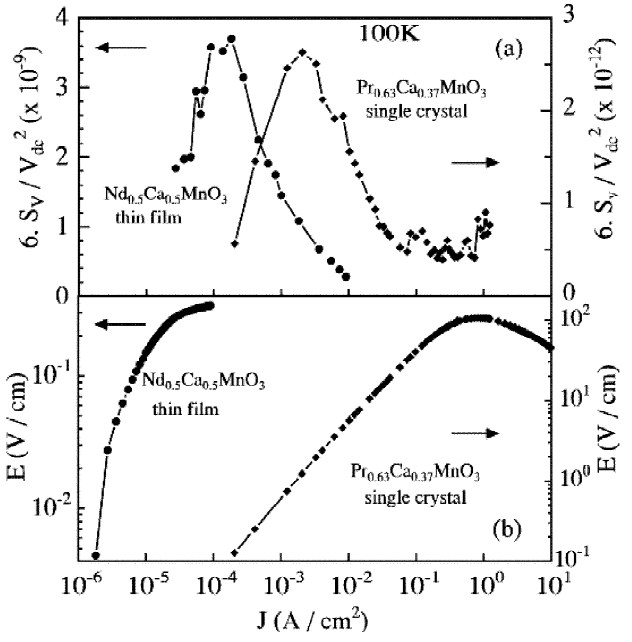

Fig. 9. Non-liner conduction (J vs. E curves) and broad band ($1/f$) noise in two charged ordered systems. (Data from Refs. [*103,104]).

between them. This gives rise to a large low frequency fluctuation. The current path becomes like a percolating network with critical cluster size. The noise spectroscopy thus can be used to study the dynamics of the coexisting phases. A closely related phenomena of CMR is charge ordering (CO), where for a certain composition the Mn^{3+} and Mn^{4+} ions arrange in a lattice in a commensurate fashion. This ordered state is unstable towards perturbations like magnetic fields or currents. Recently it was shown that a current induced destabilization leads to non-linear conductivity and large low frequency noise [*103,104]. This is shown in Fig. 9, for a CO film of $Nd_{0.5}Ca_{0.5}MnO_3$ [*103] and a CO single crystal of $Pr_{0.67}Ca_{0.33}MnO_3$ [104]. It can be seen that at the onset of non-linearity (seen in the J–E curve) the noise shows a large increase.

Application of noise spectroscopy in the field of metallic oxides is a relatively new area. However, the current trend shows that this area will grow and noise spectroscopy will become an important tool for investigating this class of materials. In particular, noise spectroscopy is a very powerful tool in assessing the stability of the material towards oxygen migration.

9. Noise in percolating system

Systems with two dispersed phases (composites) are important materials because they offer the capability to engineer properties. Noise spectroscopy has long been used to study these materials. In these materials the volume fraction of one of the phases is varied relative to the other in order to change properties. Due to the inhomogeneous nature of the solids, the current paths in these materials are not uniform. This makes the conduction susceptible to fluctuation leading to noise. These aspects of composites have been studied intensively for a decade and a half [105]. In a system of insulating and metallic phases the resistivity is strongly dependent on the volume fraction (p) of the metallic phase and near the critical volume fraction or the percolation threshold (p_c), the insulator–metal transition occurs causing a sharp drop in the resistivity. For $p \approx p_c$ the noise is a very strong function of the resistivity ρ. Generally the normalized resistivity fluctuation $S_\rho/\rho^2 (\equiv S_v(f)/v^2)$ is expected to have functional dependence on ρ. Typically it is expressed as $S_\rho \propto \rho^q$.The exponent q has been measured in a number of experiments and has been compared with theory. Good compilations of the results are given in Ref. [106]. The value of q was found to vary between 2.7 and 6. This can be compared to the prediction of the classical lattice (3D) percolation model where $q \approx 2.7$ and ≈ 4.10 for a 2D Swiss cheese type percolation model. In the insulating region where both noise and the resistivity arises from thermally activated hopping, $q = 2$ so that $S_\rho/\rho^2 =$ a constant, independent of ρ. In certain cases, described as Anderson transition, S_ρ/ρ^2 has a much stronger dependence on ρ ($\ln(S_\rho/\rho^2) \sim 1/\rho$). In a recent careful study of carbon black polymer composite, where the ρ was tuned continuously through the insulator–metal transition by changing the temperature, a clear transition was seen from $q = 2$ in the insulating side to $q = 2.77$ in the metallic side. In experiments with percolating systems, it appears that large values of q have been seen by a number of authors. One important question that has not been settled in most experiments is whether in all these materials the noise and the conductivity arise from the same source. It appears that if the two are from different mechanisms one can obtain large values of q. As an example, in an early work on Pt:Al_2O_3 composites [107] it was shown that while for conductivity the mechanism changes over from a metallic conduction (for $p > p_c$) to a tunnelling type conduction for $p < p_c$. However, in the whole range the noise is dominated by the tunnelling mechanism. In such cases one finds a large q (≈ 6). In Fig. 10 we present a collection of S_ρ/ρ^2 vs. ρ data for three composites across the percolation point. The data are for a carbon black–polymer composite [106], a Pt–Al_2O_3 composite [107] and a carbon–wax mixture [108] shown in the inset. In the Pt–Al_2O_3 system, the resistivity at percolation threshold is much less because of the metallic nature of Pt. However, if we compare all the systems shown in Fig. 10, no 'universal behaviour' seems to emerge from the data although one may observe a power-law dependence of S_ρ/ρ^2 on ρ. It is expected that experiments that can fine tune the transition as in Ref. [106] can lead to clean data.

An interesting question is whether the noise diverges near the insulator–metal transition. There are conflicting

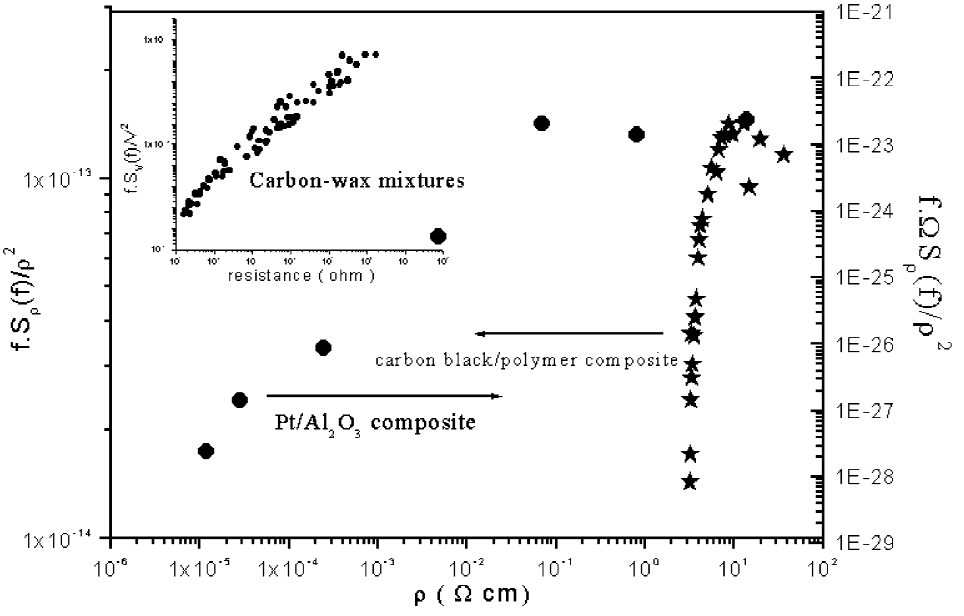

Fig. 10. The dependence of the scaled noise S_ρ/ρ^2 on the resistivity ρ near the percolation threshold. (Data complied from Refs. [106–108]).

reports. In the Pt:Al_2O_3 and carbon black–polymer systems evidently the noise does not diverge although it rises as the percolation threshold is approached. In contrast, in the carbon–wax system it was found that the noise diverges and jumps by nearly six orders of magnitude at the composition at which the resistivity jumps by three orders.

Another important issue in the study of composites is the inhomogeneous nature of the current paths. It is clear that current in these materials does not flow homogeneously given the inhomogeneties in the resistivity. As a result there will be regions that will have more effect on the conduction noise than other regions. This question has been addressed in the context of *a*:Si as discussed before. New techniques are proposed to investigate these issues [28]. It is expected that such probes will add a new dimension to the use of noise spectroscopy in materials research.

Near the percolation threshold the conduction can become non-linear and there are added features to the $1/f$ noise. Non-linear conduction and $1/f$ noise near the percolation threshold has been studied in carbon–wax mixtures [109].

Investigations of composite materials will remain a fruitful area and with addition of new tools to analyze the data it is expected that such issues as inhomogeneous current flow will be addressed. The carbon–wax/carbon–polymer systems have been used as model systems for a long time. It will definitely be profitable to investigate other well-defined percolating systems and this will make noise a more viable tool in the study of these important classes of materials.

10. Concluding remarks

In this review, we have discussed some of the fundamental aspects of noise and some examples of its applications in materials science. Noise is a sensitive probe of the defects in a solid and it has been amply demonstrated by investigations over the last one and half decade that noise is a powerful tool of materials research. Utility and usability of noise spectroscopy is no longer the issue that need be established, To make noise an even more powerful tool it will be necessary for future investigations to focus on the following four issues. Firstly, there is a need to make noise measurements more reproducible by fixing the background noise and its subtraction more effectively and to eliminate contact noise. Secondly, there is a need to do more controlled experiments with well-characterized samples and defined defects where a quantitative connection can be established between the origin of noise and the noise itself. Briefly, the noise investigations have to transcend qualitative measurements and loose correlations. Thirdly, there is a scope to make noise measurements more informative through utilisation of tools like non-Gaussianity and second spectra, etc. Fourthly, it will be immensely profitable if the noise measurements can be innovatively combined with other measurements.

We have briefly discussed noise spectroscopy in metals, semiconductors, metallic oxides and inhomogeneous systems. This is definitely not exhaustive. There is a clear positive trend to make noise measurements more useful and more informative. Application potentials like reliability study and failure prediction will boost the practice of this field.

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