CHAPTER 3

1/f NOISE SOURCES IN HOMOGENEOUS SEMICONDUCTORS

The preliminary ideas regarding the basis of 1/f noise have been briefly dealt in chapter 2. In the present chapter the ideas put forward by Hooge [1] are presented in detail since the present studies are based on the discussion presented by Hooge [1]. For convenient the notation offered by Hooge is adopted with minor changes so that the notations offered in chapter 2 are mostly adopted. However distinct notations for the same physical parameter are avoided as far as possible. The 1/f noise model can be adopted to semiconductor devices (with modifications), if the model is successful in the prediction of 1/f noise in bulk semiconductors.

The Noise output in any device can be regarded as a sum of contributions from many sources - modified by the device characteristics. The device may introduce coupling between different contributions. If a reliable model of the device is known, the exact sources are identified and the coupling mechanism between various sources is known, the noise output of the device can be evaluated. If the calculated value is in agreement with the measured value, within the experimental limitations, the model so adopted is said to be successful.

Conversely starting from the experimentally observed output noise, the nature and exact sources of 1/f noise can be predicted. It has been mentioned [1] that this method is to be adopted cautiously. The following precautions are to be adopted:

1) A correct 1/f noise model has to be adopted which has successfully explained the nature of 1/f noise in several studies (using various devices and experimental conditions).

2) The experiments are performed under normal conditions as recommended by the models adopted for the study. If different models are being tested, the combined conditions of testing are to be fulfilled.

3) This method being secondary, new propositions are to be made cautiously and after performing several confirmatory tests.

In view of the above facts, the properties of noise sources can be best studied on samples of homogeneous semiconductor devices. The numerical results so confirmed can be used for inhomogenous (or nonlinear) devices. The first step towards the 1/f noise study is perhaps to evaluate the parameters connected with homogenous semiconductor devices.

3.1 Important Types of Noise in Semiconductors:

In semiconductors the following four types of noise are of importance [1]. Some of these are 1/f type and others are of different type.

3.1.1 Thermal Noise: Due to variation of thermal electrons (or holes) every media shows spontaneous current (or voltage) fluctuations. The current, I, through (or voltage V across) the device accordingly fluctuates. The fluctuating quantity (denoted by S_I) is expressed as

$$S_I = 4 \, k \, T \, /R \qquad (\text{or } S_V = 4 \, k \, T \, R) \qquad \qquad ... (3.1)$$

where R is the noise free resistance, k the Boltzmann constant. This is known as thermal noise and is always present in every system. At constant temperature its magnitude remains constant and do not depend on the size and shape of the semiconductor. Its spectrum is white and present when current is dissipated. Several studies are available in literature.

3.1.2 Shot Noise: The electrons that cross a potential barrier in a semiconductor (or the current carried by electrons emitted from a hot cathode in a vacuum tube) are generated in random. The random generation of the electrons result into fluctuations in average current I and is given by

$$S_I = 2 \, qI \qquad \qquad \cdot \qquad \qquad ... (3.2)$$

where q is a coefficient of shot noise. This noise is found to be independent of the emission process provided the electron interaction is absent. The emission is in accordance with Boltzmann distribution and well understood.

3.1.3 Generation-recombination Noise: In semiconductors the conduction is due to electrons and holes. The number of electrons in the conduction band (or holes in the valence band) at any instant are not constant. Their number from time to time due to simultaneous generation and recombination at bands and traps respectively. At a given temperature the average number of carriers are assumed to be constant. However their instantaneous value do not remain constant. The fluctuating number of carriers lead to fluctuation in conductance G (or associated resistance R), and is given by

$$S_R/R^2 = S_G/G^2 = S_N/N^2 = (\Delta N)^2/N^2 \quad 4\tau/(1 + \omega^2 \tau^2) \qquad ... (3.3)$$

where τ is relaxation time (which is essentially the characteristic of trap), usually lies in the range 10^{-6}s to 10^{-3}s. If there exist only one type of trap present in semiconductor, the variance $(\Delta N)^2$ is given by

$$1/(\Delta N)^2 = 1/N + 1/X_n + 1/X_p \qquad \qquad ... (3.4)$$

where X_n and X_p are the average number of occupied traps and empty traps (respectively) present in the semiconductor. When more than one type of traps are present, the situation becomes slightly

involved. Different conditions are likely to exist that lead to simple addition of the effects of individual traps OR if concentration of certain traps are abundant compared to others, the effect of less predominate traps can be neglected.

3.1.4 1/f Noise:

1/f noise derived its name since the power spectral density of the fluctuation is proportional to $f^{-\gamma}$ where $\gamma=1.0$ +0.1 and is present in most physical systems. It is present in all semiconductors in the frequency range of 1 Hz to 10 kHz usually. It is expected that at higher frequencies (above 10 kHz) the slope γ tends to be steeper than unity. Unfortunately above certain frequency the amplitude of power spectral density falls below the value of white noise and cannot be separated. However measurements made upto 1 MHz indicate 1/f nature of spectrum [5]. Some investigators considered $f^{-1/2}$ and $f^{-3/2}$ as 1/f noise in certain physical systems. It has been observed that such power spectra occur from diffusion process in semiconductors. Hence these powers would not be considered as 1/f noise in the present study.

The sources mentioned in 3.1.1 to 3.1.3 are well understood. The origin of 1/f noise is still open to debate. There have been many controversies [6-11]and the debate is still on. In the present study our interest is in 1/f noise and its nature at room temperature in selected devices. Usually temperature influence is discussed to analyse the physical nature of 1/f noise, when the theoretical basis is set. The noise due to hot electrons is not considered. Since attempts have been made to establish the physical model, we restrict our investigation to the derivation of numerical values and discuss the validity of the model within the experimental constraints.

Perhaps the first systematic study on 1/f noise was initiated [12] by collecting data on 1/f noise from literature. The data so collected showed systematic trend of α was found and the factors influencing this factor could not be exactly identified. However, it seemed reasonable to presume $\alpha = 2$ x 10^{-3} as an average value. Later when the investigations were repeated carefully and accurately (by also improving the quality of the samples) it was found that α depends upon the quality of the crystal. This turned out to be due to the scattering mechanism that determine the mobility μ. In perfect crystals α can be 2 or 3 orders of magnitudes lower than the 2 x 10^{-3} originally proposed. It is quite essential to note that noise in semiconductors very much depend upon the physical conditions (such as growing rate, nature and purity of doping, surface treatment during and after growth and the nature of contact etc.) that were maintained while growing the crystals. When measurements were made on different samples prepared from same wafer, it was found that the spread in α was 1.5 x 10^{-3}. By making

measurements of samples prepared from different wafers taken from the same crystal it was found that the spread is much wider. The measurements made from different laboratories (of similar samples) were compared, it was found the spread is much wider. It was further concluded that there exits a definite dependence of α on μ which can be determined when experiments are performed carefully. The α value for samples without impurities (α_{lim}) were extrapolated from different sets of the above mentioned experiments which yielded values within 10% (of the values obtained by a different setup) even though individual α values differ by a value 1.5 x 10^{-3}. Although homogeneous semiconductor samples do not show much influence of surface noise, it was proved that surface 1/f noise also exist in semiconductors and cannot be ignored. In MOS devices experimental 1would /f data are better explained by surface effects rather than bulk effects [14]. Noise studies in metals can also be tested assuming the same mechanism as in semiconductors. The studies in pin contact devices [15] and thin films [16] showed that similar relationship as eqn 3.5 holds. The old idea that the 1/f pertains to only semiconductors or thermionic emission as in vacuum tubes was thereby proved to be incorrect [1]. Arguments against eqn 3.5 were raised [19] because of the presence of be N in denominator. If an "average" electron is considered then N would not appear in the final result. The concept of average electron essentially considers a single electron on average [17]. A proper theory should be based on an ensemble of identical system of average electron, once this idea is implemented the ensemble number would be equivalent to electron number N and both the theories are one and the same. Weissman [18] has put forward a more serious objection. 1/f noise is usually considered as a sum of Lorentzians, leading to considering of very low frequencies. The characteristic time turns out to be $\tau \gg 1$ s. The electron must stay in the sample much longer than a few seconds in order to produce these low-frequency Lorentzian distribution [18]. When a semiconductor sample of (abnormally high) length 1 cm is considered, considering a typical diffusion coefficient D of order 10^{-3} m2/s the electron can stay for about 0.1 s inside the sample. How can such short living electrons produce noise at frequencies below 1 Hz? The answer to this problem as offered by Hooge is presented in the following lines [1]: "There is evidence that 1/f noise is due to lattice scattering. The lattice modes can scatter electrons. The scattering cross vary-section fluctuate slowly with a 1/f spectrum. There are permanently N electrons-on average-that probe the slowly varying cross section. We do not follow the individual electrons move in and out the sample; the lattice is permanent."

Having answered the theoretical objection against the factor 1/N, Hoogs fells it to be essential to investigate the experimental evidence in this regard. He states " We introduces N as measure of the size of the sample. In bigger samples the relative noise must average out. Another measure for the size may do as well, like the volume, the number of atoms A, or the number of lattice modes, proportional to A. We therefore made a comparison between N and A [19]. If the relative noise is written as

$$S_R/R^2 = \alpha/Nf = \gamma/Af \qquad \dots \quad (3.5)$$

it turns out that α is a better 'constant' than γ is. The values of α are found between 10^{-4} and 2×10^{-3}, whereas γ varies between 10 and 10^5 in a group of some twenty semiconductors. These experimental data give no argument for preferring γ/A to α/N". Hence it is more logical to study one of these variations OR to make a distinction between these to finally prefer one over the other.

To confirm the validity of α/N, the injection of a varying number of electrons in a given volume of semiconductor in a forward diode [20] and a similar experiment on photoconductivity [21] were performed. It was show that observed value of α/N is constant and lie in the range 10^{-4} and 10^{-3}. Since both the

3.2 CONDUCTIVITY - EXPERIMENTAL DISTINCTION BETWEEN Δn AND $\Delta \mu$:

There is experimental evidence to the fact that 1/f noise is a fluctuation in conductivity. Conductivity fluctuations lead to fluctuations in the resistance R. Recalling that the thermal noise is equal to $S_v = 4kTR$, the fluctuating resistance is proportional to the fluctuations in the thermal noise:

$$S_{S_v} \sim S_R \qquad \dots \quad (3.7).$$

The resistance R is measured by measuring the noise in S_v. Since no current is passed through the sample [22] it is established that 1/f noise is not generated by the current. In conventional measurements current is used only to transform the already existing conductivity fluctuations into voltage fluctuations for an easy detection and measurement. The conductivity in semiconductors is given by

$$\sigma = n q \mu \qquad \dots \quad (3.8).$$

The conductivity is a product of n and μ therefore it should be known which of these two is actually fluctuating? It was experimentally verified that exists a type of 1/f noise that fluctuates with mobility [1]. Experiments on homogeneous silicon samples estimated the order of α as 10^{-4} in perfect material. In damaged materials the mobility noise is considerably increased. On top of mobility noise there may be other types of 1/f noise such as number fluctuations at surface stages. It has been proved [1] that

number fluctuations generated at the surface play an important role in MOS's. It has also been specifically mentioned by Hooge that Δn noise predominate in N-channel MOSTs while $\Delta\mu$ noise is observed in p-channel MOSTs. In the experimental studies the ratio of the two generalised forces are varied and the magnitude of the 1/f noise is observed. The $\Delta\mu$ terms are first introduced into the transport equation, the expected fluctuations in resulting voltage or current are observed. Similar calculations are done with Δn sources. Experimental fluctuations in voltage or current due to 1/f noise (observed) are recorded. It has been shown by Hooge [1] that observed noise always agrees with $\Delta\mu$ fluctuations, in most cases "the observed noise is far off from the line for Δn fluctuations." In some calculations the values of Δn and $\Delta\mu$ "were not that far apart, so that no distinction can be made. There was no case in which the differences between observed and calculated $\Delta\mu$ values were so large that mobility fluctuations had to be excluded in favour of Δn fluctuations [22]." The 1/f noise studies in Hall effect [23] proved that the experimental points follow the $\Delta\mu$ line nicely, while $\Delta\mu$ and Δn plotted individually versus B deviated widely.

The analysis of noise in conductance of semiconductor samples, where two scattering mechanisms determine mobility can be considered [1]. Initially let the lattice and impurity contributions be responsible for observed mobility. Following Matthiessen's rule we expect

$$1/\mu_{meas} = 1/\mu_{latt} + 1/\mu_{imp} \qquad \ldots \qquad (3.9).$$

In the first case let the lattice scattering generates 1/f noise while the impurity scattering has no appreciable contribution to noise. Neglecting the impurity contribution by presuming $\Delta\mu imp = 0$, it follows that

$$\Delta(1/\mu_{meas}) = \Delta(1/\mu_{latt}) \qquad \ldots \qquad (3.10)$$

$$\alpha_{meas} = (\mu_{meas}/\mu_{latt})2\ \alpha_{latt} \qquad \ldots \qquad (3.11)$$

where α_{meas} and α_{latt} are defined by eqn 3.5. A plot between $\log \alpha_{meas}$ versus $\log \mu_{meas}$ should yield a slope of 2 according to eqn 3.11. Experimental measurements (Fig 3.1) on homogeneous semiconductor samples of different doping (with diffrent μ_{imp} contributions) showed a linear relationship between $\log \alpha_{latt}$ versus $\log \mu_{latt}$ clearly demonstrated a linear relationship indicating that 1/f noise is mobility noise.

Let the second case be discussed wherein both lattice scattering and impurity scattering be responsible for conductivity.

$$\Delta(1/\mu_{meas}) = \Delta(1/\mu_{latt}) + \Delta(1/\mu_{imp}) \qquad \dots \qquad (3.12)$$

from which it follows

$$\alpha_{meas} = (\mu_{meas}/\mu_{latt})2\ \alpha_{latt} + (\mu_{meas}/\mu_{imp})2\ \alpha_{imp} \qquad \dots \qquad (3.13)$$

assuming that

$$(\Delta\mu_{latt}\ \Delta\mu_{imp})2 = 0 \qquad \cdot \qquad \dots \qquad (3.14).$$

The plot of log α_{meas} versus log μ_{meas} is somewhat complex. If $(\mu_{meas}/\mu_{latt})2\ \alpha_{latt}$ dominates in eqn 3.13 this would lead to eqns 3.10 and 3.11 with a theoretical value of 2 to the slope of the plot as discussed in the first case. If $(\mu_{meas}/\mu_{imp})2\ \alpha_{imp}$ dominates in eqn 3.13, we have the situation where $\mu_{meas} \sim \mu_{imp}$ so that $\alpha_{meas} \sim \alpha_{imp}$. The noise characterised by α_{imp} is proportional to the number of impurity centres which turns out to be proportional to μ^{-1}_{imp} or the sme turns out to be

$$\alpha_{meas} \sim \alpha_{imp} \qquad\qquad \mu^{-1}_{meas} \sim \mu^{-1}_{imp} \qquad \dots \qquad (3.15)$$

Now a plot of log α_{meas} versus log μ_{meas} should yield a slope of -1 [1]. It is expected that both the conditions exist when the studies are made over a temperature range and different sets of curves are obtained at constant α_{imp} levels. When intersection points at constant temperature T_0 are extracted and plotted the lattice contribution dominates above certain μ_{meas} value and the slope of the plot is 2 (familiar plot discussed already) and below this μmeas level value the impurity effect dominates over lattice (Fig 3.2) and the slope of the graph is -1. The following conclusions were derived by Hooge [1]:

1. α is proportional to 'GR centers' which create a 1/f spectrum, and which do not scatter electrons, satisfying α_{meas} is proportional to μ_{0meas}.

2. σ is proportional to centers that also are scatterers of electrons: α is proportional to μ_{imp}. If $\mu_{meas} \sim \mu_{imp}$ then $\alpha_{meas} = \mu^{-1}_{meas}$

3. Just as in case 2, but with $\mu_{meas} \sim \mu_{latt}$ then α_{meas} is proportional to μ^{-1}_{imp} which in turn is proportional to μ^{-k}_{meas}, where k>>1.

Number fluctuations will always lead to negative slopes in plot of log α versus log μ ; the slope might be close to zero. The above presentation is completely based on measurements of electrical noise.
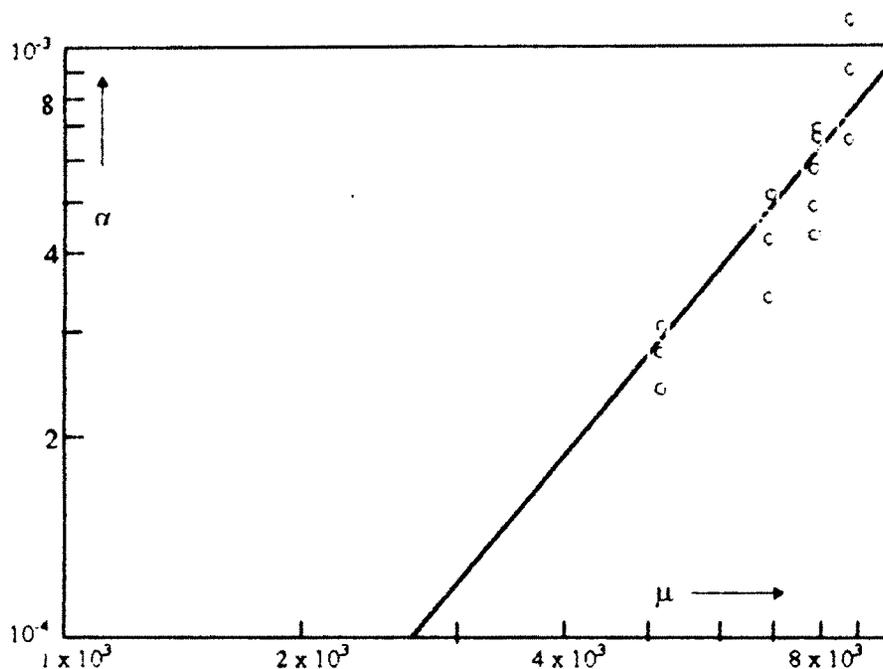
Fig 3.1 - Plot of log α_{mean} versus log μ_{mean} for epitaxial n-GaAs at 300 K measured on homogenous samples [as cited in Ref 1].
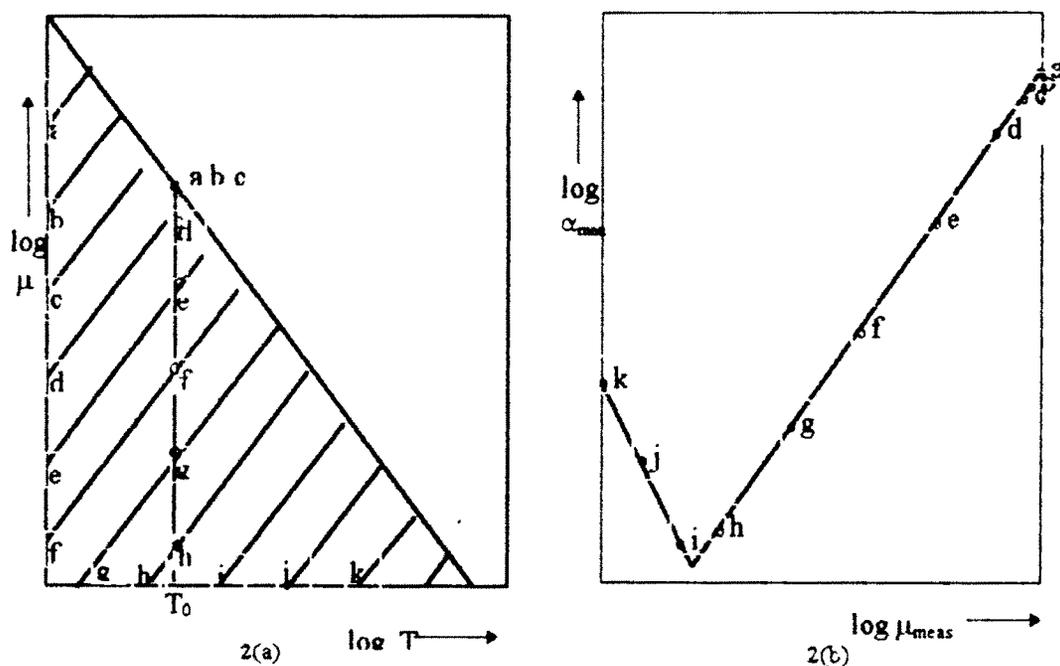

2(a)

2(b)

Fig 3.2(a) - log μ_{meas} versus log T. The impurity scattering increases by equal factors in the series of samples a to k. (b) - log α_{meas} versus log μ_{meas} at T = T$_0$. The noise of the samples d to h is determined by α_{latt} although $\mu_{meas} \sim \mu_{imp}$.

Independently in a series of optical experiments, Musha et al [25-27] showed that when photons are scattered at acoustic lattice waves the intensity of scattered light also exhibits 1/f noise. The experiments confirmed 1/f noise due to number fluctuations.

3.3 1/f Noise - Δn Models

All Δn models are based on the same principle that the addition of the Lorentzian GR spectra with a special distribution of relaxation times τ_i. A very wide range of τ_i values is require [1]. A 1/f spectrum is obtained between the frequencies $1/\tau_2$ and $1/\tau_1$ if $\tau_1 < \tau_i < \tau_2$. Below $1/\tau_2$ the spectrum is white and above $1/\tau_1$ the spectral density is proportional to f^2. On using normal distribution $g(\tau_i)$, as shown in Ref[1]

$$g(\tau_i) = 0 \qquad \text{for} \quad \tau_i < \tau_1 \qquad \qquad \ldots \quad (3.16)$$

$$g(\tau_i) = 1/\ln(\tau_2/\tau_1)/\tau_i \qquad \text{for} \quad \tau_1 < \tau_i < \tau_2 \qquad \ldots \quad (3.17)$$

$$g(\tau_i) = 1/(\ln \tau_2/\tau_1) \cdot 1/\pi^2 \tau_i \quad \text{for} \quad \tau_2 < \tau_i \qquad \ldots \quad (3.18)$$

$$S_N = (\Delta N)^2 \quad g(\tau_i) \cdot 4\tau_i / (1 + \omega^2 \tau_i^2) \, d\tau_i$$

$$= (\Delta N)^2 \; 4/(\ln \tau_2/\tau_1) \; 1 / (1 + \omega^2 \tau_i^2) \, d\tau_i$$

$$= (\Delta N)^2 \; 4/(\ln \tau_2/\tau_1) \; \arctan \omega\tau_i \big|_{\omega\tau_2}^{\omega\tau_1} \qquad \ldots \quad (3.19)$$

for $\omega \ll 1/\tau_2 \ll 1/\tau_1$; $S_N = (\Delta N)^2 \; 1/(\ln \tau_2/\tau_1) \; 4\tau_2$ $\ldots$ (3.20)

for $1/\tau_2 \ll \omega \ll 1/\tau_1$; $S_N = (\Delta N)^2 \; 1/(\ln \tau_2/\tau_1) \cdot 1/f$ $\ldots$ (3.21)

for $1/\tau_2 \ll 1/\tau_1 \ll \omega$; $S_N = (\Delta N)^2 \; 1/(\ln \tau_2/\tau_1) \cdot 1/\pi^2 \tau_1 \, f^2$ $\ldots$ (3.22)

In the above equations the approximations

$$\arctan \delta = \delta \qquad \text{and} \qquad \arctan (1/\delta) = \pi/2 - \delta \qquad \ldots \quad (3.23)$$

are used. The trap distribution eqn 17 only leads to a 1/f spectrum if "there is no transition between traps with different τ's neither directly nor via the conduction band. The case of isolated traps support eqn 3.21. A fluctuation in the number of free electrons decays by interaction with all traps [1]:"

$$1 \, \Delta X/dt \sim \Delta X/(\ln \tau_1 / \tau_2) \cdot 1/\tau_1 = \Delta X/ \tau_0 \qquad \ldots \quad (3.24)$$

where τ_0 is defined as

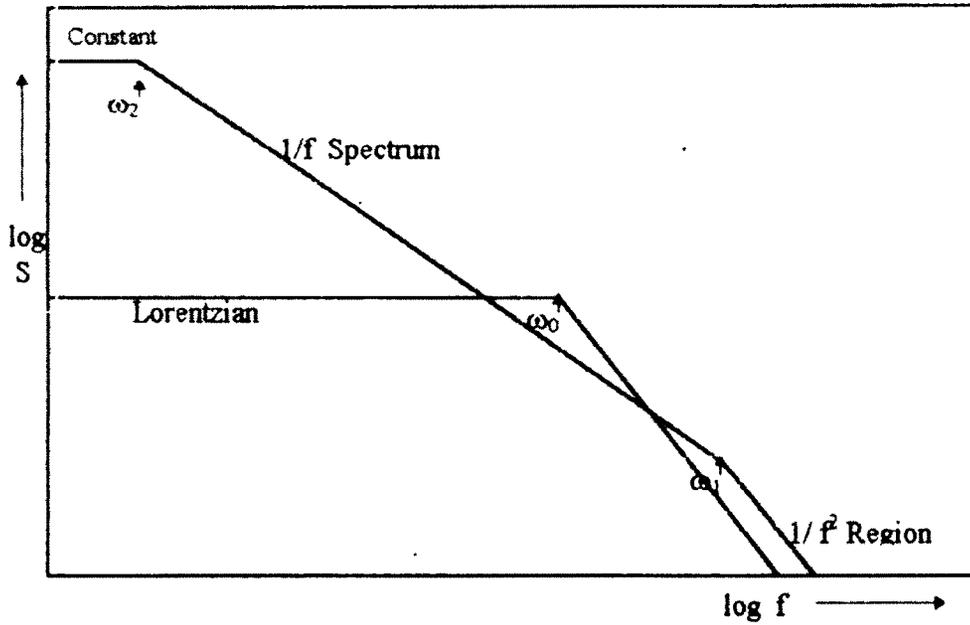$$\tau_0 = \tau_1 \ln \tau_2/\tau_1 \qquad \qquad \ldots \quad (3.25).$$
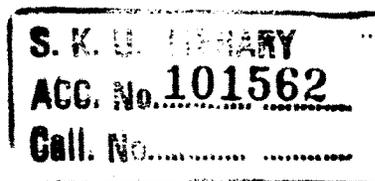
Fig 3.3 - The Lorentzian resulted due to interacting traps with a characteristic frequeny ω_0 and 1/f spectrum is due to isolated traps with characteristic frequencies ω_1 (higher) and ω_2 (lower). The Lorentzian intersects the 1/f line at $1/2\pi\tau_0$ for $\tau_2/\tau_1 = 5 \times 10^8$ or $\tau_0/\tau_1 = 20$.

The one single Lorentzian is obtained with a characteristic frequency $f_0 = 1/2\pi\tau_0$ which rolls off above the frequency $f = 1/\tau_0$ due to interacting traps while a $1/f$ spectrum is observed due to isolated traps. Irrespective of the type of $g(\tau_i)$ chosen, a single Lorentzian is obtained due to the average τ.

A distribution $g(\tau)$ is proportional to α is easily realised over a wide range over a wide range of τ values, if τ exponentially depends on a quantity that is homogeneously distributed over a limited range.

For instance, in McWhorters surface model, traps are assumed to be homogeneously distributed in the oxide layer on a semiconductors. The probability $1/\tau$ of an electron in the semiconductor reaching a trap in the oxide layer by tunneling is given by

$$\tau = \tau_0 \, e^{\,x/d} \qquad\qquad\qquad \dots \quad (3.26)$$

where x is the distance from the trap to the silicon oxide interface, and d is a constant characteristic for the tunnel process.

$$g(\tau) = DN/d\tau = DN/DX \, . \, DX/d\tau \qquad 1/\tau \qquad\qquad \dots \quad (3.27)$$

N is the number of traps DN/DX the concentration of traps which is constant.

The St. Petersburg group [28] has proposed a special model for gas, with a tail of states below the conduction band. The density of states in the tail is assumed to be exponential

$$N(E) = N(0) \, e^{\,-E/E^*} \qquad\qquad\qquad \dots \quad (3.28)$$

where E is the distance of the state to the bottom of the band. For the relaxation time of the state as cited in [1] it was assumed that

$$\tau(E) = \tau(0) \, e^{\,-E/kT} \qquad\qquad\qquad \dots \quad (3.29)$$

The result is again $g(\tau)$ $1/\tau_1$.

The required distribution $g(\tau)$ $1/\tau$ can be obtained with process that are thermally activated. If E_1 is homogeneously distributed between E_1 and Eh_k, and if $g(E)$ is zero outside this interval, then an exact $1/f$ spectrum is obtained at frequencies f between

$$1/\tau_h \; < \; 2\pi f \; < \; 1/\tau_1 \qquad\qquad\qquad \dots \quad (3.30).$$

In the Dutta Horn model [29, 30], $g(E)$ need not be a constant. A peak of E values a few kT wide is good enough to produce a $1/f$- like spectrum: $f^{-\gamma}$ with $\gamma = 1 + 0.3$. The slope will not be constant over the whole frequency range, and there will a relation between slope and temperature dependence of the spectral power:

$$\gamma(\omega,T) = 1 - 1/\ln(\omega\tau_0) \; \{[d \ln S(\omega, T)/ d \ln T] - 1\} \qquad \qquad \ldots \qquad (3.31)$$

where $\tau_0 \sim 10^{-14}$ s, an attempt time in the order of an inverse phonon frequency.

The essence of the Dutta Horn model is that a wide range of τ's results from a rather narrow peak of activation energies. The width of the peak is determined by the disorder in the crystal. Our question now is : "Is this of interest for semiconductors at room temperature?"

In applying the model directly to generation recombination noise the activation energies of the traps will be 0.3 eV at most. The width of the peak could then be of the order of 0.03 eV. Hence $\Delta E/kT$ is of the order 1. So there is no appreciable frequency range in which a 1/f spectrum can be observed. The Dutta Horn model is of little interest to number fluctuations at room temperature, but it can be applied to mobility fluctuations.

3.4 1/f Noise - $\Delta\mu$ Models

We shall present two theoretical models for mobility 1/f noise: 1) Local interference Noise, 2) Quantum 1/f noise. No critical discussion of the theories will attempted; the emphasis is on results which can be used in discussion on the noise of devices.

3.4.1. Local Interference Noise

This is one of the three cases where Dutta Horn model is applied to mobile defects that act as scattering centers for the electrons [31]. The local interference model has been very successful in the study of noise in metals, especially in disordered metal films [32, 33]. Here our problem is whether it can be of interest for semiconductors at room temperature. We shall mainly be guided by Giordano's review [32].

The principle can be sketched as follows. An electron returns to its original position after a random walk during which it has been scattered by several scattering centers, in this case lattice defects. Each scattering event gives a phase shift. The electron arrives at the original position again with a certain phase shift in its wave function, it has traveled the same path, but in opposite direction, its final phase shift have been the same as for the original direction. So there is constructive interference. the electron density at the original position is higher that for two uncorrelated functions.

Now the conductance between A and B is seen as a summation of all possible paths from A to B. via all scattering centers. The phase is preserved over a limited distance L_ϕ . In the universal conductance fluctuation model (UCF), the multiple scattering events of all defects in L^3_ϕ contribute to

the interference. After a defect has moved to a different position, the conductance is different, which is interpreted as mobility noise. The defects have somewhat different activation energies for jumping, and therefore, different τ values. The summation of the individual Lorentzians yields a 1/f spectrum, according to Dutta Horn model. The UCF noise is found in a crystal in high degree of disorder at very low temperatures.

The local interference model (LI) applies to electron waves singly scattered by a few neighboring defects. A special case of LI is the two level system (TLS), where the scatterer moves from one position to an energetically equivalent second position by tunneling through an energy barrier. Also in the LI model, the defects moves with nearly the same activation energy, giving a 1/f spectrum by summation of Lorentzians. The LI model predicts 1/f noise at room temperature in weakly disordered metals.

One might think that the degree of disorder required is not to be found in nearly perfect epitaxial semiconductor films. Even though this may be true, it cannot be used as an objection against the LI model. The noise intensity α, is proportional to nn_{md}, where n is electron density and n_{md} the density of the mobile defects as cited in [32]. In metals we find that therefore, $\alpha \quad nn_{md}$ to An_{md}, where A is number of atoms per cm^3. In semiconductors we find α is proportional to n, when we investigate differently doped samples made from the same host material, with the same n_{min} all samples. So there is no problem with the low value of n_{md}/A in high quality semiconductors. The problem is rather that α would depend on n, contrary to all experimental evidence. LI seems not to apply to semiconductors.

A second argument against LI is that in semiconductors the exponent of spectrum is 1.0 not 1+ Δ, as would result from the use of the Dutta Horn procedure in the local interference model. We know of one interesting example where the LI model might apply to semiconductors: proton irradiated GaAs at low temperatures (T < 150K). Ren found a practically temperature independent noise, proportional to the radiation dose. There is a small peak in ln α versus 1/T. Agreeing with the slope γ, which is not exactly -1. Here eqn 3.31 holds [34]. The temperatures of the peaks correspond to 0.35 eV.

Irradiation of samples that were originally doped with different donor concentrations shows that this is mobility noise. Since $\alpha \quad \mu^2_{mean}$ [35]. However, the quadratic dependence is characteristic of lattice scattering where as the LI model is based on impurity scattering.

3.4.2 Quantum 1/f Noise

The quantum 1/f noise is briefly dealt in this chapter to express views of Hooge [1] regarding this special effect. However, it is dealt in detail in Chapter 4.

All tree models UCF, LI, and TLS deal with interference of waves scattered at many centers. Hence the spatial arrangement of the centers changes, we observe a change in the conductance, noise. Handel's model is more general: there are 1/f fluctuations in each scattering event at each individual scattering center [36]. In a excellent review paper [37] VanVliet does away with many later additions of the original model. But the essential idea still stands: interference between the Bremstrahlung and non-Bremstrahlung part of the electron wave function.

In the scattering process a low frequency photon is absorbed or emitted. The wave length of such a photon is much longer than the dimensions of samples and of Faraday cages. The question is: can such photons be present or developed in this limited space? This is the so called cage effect, which is not accepted as a serious problem by VanVliet [38]. This may be correct, but then there is no way of coming to grips experimentally with these photons. "They are lost to the universe." The model is so general that there are no specific features that lead themselves to experimental confirmation. Due to this general nature and because of the most characteristic participants - the low frequency photons - cannot be studied, nothing else is left to us than to compare numerical results of model and experiment. Handel's model predicts the following α values.

Handel cites some experimental α values to support the theoretical results. All experimental values but one, are derived from noise studies of devices. The exception is Bisschop's work on polysilicon. His values 10^{-9} - 10^{-8} are, however, not α values at all [42]. Some more details of quqntum 1/f noise are presented in Chapter 4.

Comparison of theoretical values with the experimental values lead to the conclusion that the experimental results do not support Handel's theory. It could very well be that theoretical model correctly predicts some kind of 1/f noise, but then this type of 1/f noise is different from the observed noise with a much higher α.

3.4.3 1/f Noise and Empirical Values

In proposing a model for the 1/f noise in devices, two kinds of assumptions for the sources must be made. These are assumptions about 1) Their physical nature: Δn or $\Delta \mu$, isolated or interacting traps, bulk or surface states, etc. 2) The numerical value of α (mobility fluctuations considered).

Hooge has compiled or collected α_{mean} and α_{latt} of earlier surveys on silicon [9, 10 and 43] and experimental results on GaAs [44 & 45] to deduce empirical relations. He deduced in GaAs the following expression

$$\alpha_{latt} = 0.1 \exp[-0.13 \text{ eV/kT}] + 7 \times 10^{-5} \qquad \qquad ...(3.32)$$

Similar empirical relations can be derived in silicon or other semiconductors or the compound semiconductors. It has been concluded that for silicon $\alpha = 10^{-4}$ instead of $\alpha = 2 \times 10^{-5}$ that has been hitherto used. It is also pointed out that low values of α measured is not the indication of purity. If $(\mu_{meas}/\mu_{latt})2$ is small then α_{meas} is likely to be measured low.

Damaging the crystal by mechanical stress or by irradiation strongly increases the 1/f noise. The electron concentration and the mobility hardly change; nevertheless the noise increases by orders of magnitudes. The first explanation that comes to mind is that the defects act as generation recombination centers which in some, as yet unexplained, may generate 1/f noise. If this is correct then the induced noise is fluctuation in the number of free carriers. However, it might also be possible that the defects act as scattering centers. If they are mobility will generate 1/f noise according to the local interference model. Therefore, one would like to see further investigations of the induced noise in damaged material, e.g a plot of log $\alpha_{induced}$ versus log μ_{meas}, because that would decide whether the induced noise is mobility noise or number noise. In case of mobility noise it is important to distinguish between impurity scattering- agreeing with the LI model - and lattice scattering, as has possibly been found with proton irradiated GaAs [35].

The relation between i/f noise and damage has been critically reviewed in an extensive review by D'yakonova, Levinshtein, and Remyantsev [28]. The model favoured by the authors is that the defects create the states in the tail below the conduction bond. This experimental support for this model from measurements of photo conductivity.

Papers dealing with noise and damage, that appeared after this survey follow the lines of thinking of the survey [46-52]. It is immediately assumed that all authors - except one - that the induced noise is number noise. Based on this assumption sum model for the generation recombination centers is then presented without experimental evidence conforming the number fluctuations and excluding mobility fluctuations the exception is Ren [35] who plotted mean versus μ_{meas} of the 1/f noise induced by proton irradiation of GaAs. He found that the noise was mobility noise.

3.4.4 Conclusions: Hooge's analysis establishes the following conclusions [1].

1) In all semiconductors there always is mobility 1/f noise with an α value of 2×10^{-3} to 10^{-4} Other types 1/f noise may be present and may dominate the mobility noise.

2) $\alpha_{meas} = (\mu_{mean}/\mu_{latt}) \, \alpha_{latt}$

where mean directly follows from the empirical relation [7] and α_{latt} is the value that would have been found if lattice scattering only were present. This means that the lattice scattering is the origin the mobility 1/f noise.

3) Damaging the crystal increases the 1/f noise considerably where as the mobility hardly decreases.

4) Each of the two values, α_{latt} and α_{meas}, has its own field of application. We need α_{meas} if we want to propose a noise model of a device. We need α_{latt} in comparison with theoretical predictions and in assessments of the quality of semiconductor material.

CHAPTER 4 - REFERENCES

1 F N Hooge, "1/f Noise Sources", IEEE Trans Electron Devices, 41, pp 1926-1936(1994).
   F N Hooge and L Ren, "On the Generation Recombination Noise", Physica, B191, p220(1993).
   F N Hooge and L Ren, "On the Generation Recombination Noise", Physica, B193, p31(1994).
2 K M van Vliet and J R Fasset, "Fluctuations due to electronic transitions and transport in solids", in Fluctuation Phenomena in Solids (Ed R G Berger), New York , Academic Press, p 267(1965).
3 AD van Rheenen, G Bosman and CM van Vliet, "Decomposition of Generation-Recombination Noise Spectra in Separate Lorentzians", Solid State Electron, 28, p 457(1985).
4 K Kandiah, "Random Telegraph Signal Currents and Low Frequency Noise in Junction Field Effect Transistors", IEEE Trans Electron Devices, 41, pp2006-2015(1994).
5 TGM Kleinpenning and AH de Kuijper, "Relation between Variance and Sample Duration of 1/f Noise Signals", J Appl Phys, 63, p 43(1988).
6 Proc. 7th int.conf. on noise in physical systems, And the 3rd int. Conf. On 1/f noise, Montpellier France, May 1983 , (Ed M.. Savelli, G. Lecoy and J.P.Nouger). Amsterdam: North-Holland,(1983).
7 Proc. 8th int. Conf. On noise in physical systems and 4th int. Conf on 1/f noise, Rome, september 1985; (Ed A.D'Amico and P.Mazzew) Amsterdam: North-Holland, (1986).
8 Proc. 9th int. Conf. On noise in physical systems ,Montral, May 1987, (Ed C.M.Vanvliet) Singapore : world scientific (1987).
9 Proc. 10th int. Conf. On noise in physical systems, Budapest, Aug 1989, (Ed A. Ambrozy), Budapest : Akademiai kiodo. (1990).
10 Proc. 10th int. Conf. On noise in physical systems and 1/f fluctuations Kyoto, Nov 1991, (Ed. T.Musha, S. Sato, and M. Yamamoto. Tokyo: Ohmsha Ltd., (1991).
11 St. Louis, " Noise in physical systems and 1/f fluctuations" AIP conf. Proc., 285, (Eds P.H. Handel and A.L.Chaung) New York: AIP Press 1993.
12 F.N. Hooge, "1/f noise in no suface effects" Phys.Lett., 29A, p. 139 (1969)

13 A L Mc Whorter, "1/f noise and related suface effects in germanium " Ph.D dissertation, MIT, Cambridge, MA, (1955).

14 L.K.J. Vandamme, "Bulk and surface 1/f noise," IEEE Trans electron devices, 36, p,987 (1989)

15 A.M.H. Hoppenbrouwers and FN Hooge,. "1/F noise of spreading resistances, " Philips Res. Rep., 25, p 69 (1970).

16 F N Hooge and A M H Hoppenbrouwers, "1/f noise in continous thin gold films" Physica, 145, p,386, (1969).

17 F N Hooge, " on expressions for 1/f noise in mobility ,"physica, B114,. P.391,(1982).

18 M B Weissman, "1/f noise and other slow, non exponential kinetics in condenced matter",Rev, modern physics., 60, p.537(1988).

19 F N Hooge "The relation between 1/f noise and number of electrons," Physica, B162, p 344 (1990).

20 TGM Kleanning, "1/f noise in pn diodes" physica, B98, p 289(1980)

21 F Hofman and RJJ Zijlstra, "the validity of Hooge's law for 1/f noise" , solid state commun., 72, p.1163(1989).

22 F N Hooge, TGM Kleanning and L.K.J. Vandamme, " Experimental studies on 1/f noise" Rep. On progessin physics, 44, p479(1991).

23 L Ren and JS Liberis, "1/f noise in the Hall voltage of epitaxial n-GaAs",physica, B183, p.40(1993).

24 M Tacmo, "Hooge parameter determined by impurity scattering," In [11] p.9

25 T Musha, G Bobely and M Shoji, "1/f phonan number fluctuations in quartz obsevved by laser light scattering",phys. Rev, Ltt., 64, p2394(1990).

26 T Musha and G Bobely, "1/f fluctuations of phonon energy in water" jap. J. Applied physics, 31, p.370 (1992).

27 T Musha, K Takada and K Nakagawa, "fluctuatins of light intesity scattered by aqueous LiCl solution", [11], p.141.

28 N V D' yakonova, M E Lenshtian, and S L Remyantsev, "nature of the bulk 1/f noise in GaAs and Si (review), sov. Phys, Semiconducters, 25, p 1241 (1921).

29 P Dutta, P Dimon, and PM Horn, " Energy scales for noise processess in metals", phys Rev Ltt. 43, p 646 (1979).

30 P Dutta and PM Horn, " Low frequency fluctuations in solids: 1/f noise," Rev. Modern Phys., 53, p 497 (1981).

31 M Kogen and K E Nageev, " On the low frequency current 1/f noise in metals," solid state commun,. 49, p. 387 (1984).

32 N Giordano."Defect motion and low frequency noise in disordered metals," Rev. Solid state science, 3, p 27 (1929).

33 J Pelz and J Clark, "Quantitative local interference model for 1/f noise in metal films," phys Rev, B36, p.4479 (1987).

34 L Ren "Intrensic and extrensic 1/f noise sources in proton irradiated n-GaAs epitaxial layers," Appel. Phys, 74, p.4534 (1993).

35 L.Ren FN Hooge "Intrensic and extrensic 1/f noise sources in proton irradiated n-GaAs," in [11], p.65.

36 P J Handel. "1/F noise - an infrared phenomenon," Phys Rev Lett vol 34, p.1492 (1975)

37 CM van Vliet, " A survey of the results and the future prospects on quantum 1/f noise and 1/f noise in general ", solid state Electron., vol 34 p 1 (1991).

38 CM Van vliet "Further comments on Handels theory of Quantum 1/f noise," Physica, A 150, p 244 (1988)

39 GS Koushik, CM Van vliet. Bosman, and P H Handel "Quantum 1/fnoise asssociated with ionised impurity scattering and electron phonon scaterring in codensed matter," Advances in physics, 34, p 663 (1985).

40 GS Koushik, CM Van vliet. Bosman and H J Luo, "Quantum 1/fnoise asssociated with inervalley scattering in non-degenerate semiconducters,"Physica status solidi vol b 154 p 713, (1989).

41 PH Handel Chung, "Graphical representation of quatum mobility fluctuation spectra in sillicon," in[11], p 176.

42 J chop " Experimental study on the 1/f parameter α," Ph.D dissertation university, Eindhoven p64 (1983).

43 FN Hooge and M. Tacano, "Experimental studied of 1/f noise in n-GaAs," physica, B190, p 145 (1993)

44 L Ren and MR Leys "1/f noise at room temperature in n-type GaAS grown by molecular beam epitaxy," Physica, B172, p319 (1991).

45 L Ren and FN Hooge, " Temperature dependence of 1/f noise epitaxial n- type GaAs physica, B176, p 209, (1992).

46 M E Levinshtein and S.L Rumyantsev, " Relaxation of photo conductivity and 1/f noise subjected to damaging compressions," Soviet physics, 25, p97 (1991).

47 NV D'yakonova, M E Levinshtein and S.L Rumyantsev,"Temperature dependece of low frequency noise in structerraly perfect GaAs and after destructive compression", sov Physics, senmiconducter, 25, p217 (1991)

48 LS Bakshi, EA Salkov and BI Khizhnyak ,"1/f noise in HgCdTe converted from n-to p-type by native doping" solid state commun,l 81 p 781 (1992)

49 LS Bakshi, LA Karachevsta, AV Lyubchenko, VA Petryakov, EA Salkov and BI Khizhnyak," influence of compensating annealing on the 1/f noise in CdHgTe," Soviet Phys, Semiconducter, 26, p 97 (1992).

50 GM Gusinskii, NV D'yakonova, M E Levinshtein and S.L Rumyantsev"Noise of the 1/f type and electrical and photo prpoperties of GaAs bombarded with high energy ions", Soviet Phys Semicond., 26, p 307 (1992)

51 Yu M Galperin and VI Kozub,"Disorder induced flicker niose in small structures, Normal and super conducting state" in [11] p 39

52 NV D'yakonova, M E Levinshtein and S.L Rumyantsev, " Nature of the 1/f noise in GaAs Si," in [11] p 593

53 W J Zheng and XC Zhu, " The contribution of electrode to /f noise in SPRITE LWIR detecters" in [11] p 448.

54 W J Zheng and XC Zhu, " Experimental studies on low frequency noise of HgCdTe photo conducters,", Infrared Physics vol 33 p27 (1992)

55 M de Murcia, F Pascal, G Lecoy, and LKJ Vandamme,"Excess noise in ALGaAs epitaxial layers" in [11] p31

56 S Jarrix, C Delseny ,F Pascal, G Lecoy and J dangla ,"Low frequency noise in P$^+$ - GaAs resistors," Electronic letter,l 29, p1571 (1993).

57 Hei Wong and Chung Cheng,"Modeling of Low-Frequency Noise in Metal-Oxide-Semiconductor Field-Effect Transistor with Electron Trapping - Detrapping at Oxide -Silicon Interface", IEEE Trans Electron Devices, 38, pp1883-1888(1994).