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Noise Spectroscopy and Defect-State Characterization in Amorphous Semiconductor Thin Films

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Abstract

Amorphous semiconductor thin films have a large number of localized defect states and dangling bond centers which have significant effects on carrier fluctuations and electronic stability. This work focuses on the application of power spectral density analysis and relaxation spectroscopy to study the low-frequency noise and defect-state characterization in a-SE thin films. Noise measurements were made over a broad bandwidth of frequencies and temperatures to examine the fluctuations of the carriers associated with localised trap states in the micro regime. The noise spectra showed that the major noise component was the 1/f noise and Lorentzian components were associated with generation–recombination processes and defect-state relaxation dynamics. The frequency exponent and the spectral density were seen to have strong temperature-dependence, signifying strong coupling between the carrier transport and the dangling bond defects present in the amorphous network. The noise magnitude and relaxation intensity were decreased with the application of thermal annealing because of partial passivation of localized defect states. The study shows that the noise spectroscopy technique is a useful non-destructive technique to determine the defect density, fluctuations of carrier lifetime and the transport stability of amorphous semiconductor materials.

Keywords: Noise spectroscopy, amorphous semiconductors, defect states, dangling bonds, 1/f noise, power spectral density, relaxation dynamics, thin films.

1. Introduction

Amorphous semiconductor materials have become technologically important electronic materials because of their wide range of applications in thin-film transistors, photovoltaic devices, optical detectors, image sensors, memory devices and flexible electronic systems. Unlike crystalline semiconductors with a long range periodic arrangement of atoms, amorphous semiconductors are characterized by the absence of long range periodicity, and have a network of disordered atoms. This structural disorder leads to the formation of local states, defects involving dangling bonds, imperfections in the way the atoms are coordinated and to a distribution of trap centers throughout the mobility gap of a material. The localized defect states significantly affect the electrical, optical and transport characteristics of amorphous semiconductors and they have a significant impact on the dynamics of the carriers and on device stability.

Amorphous silicon (a-Si), hydrogenated amorphous silicon (a-Si:H), amorphous germanium (a-Ge) and amorphous selenium (a-Se) are among the most studied amorphous semiconductor materials. The benefits of these materials are that they are inexpensive to fabricate, can be deposited on a large scale, are mechanically flexible and can be processed at low temperatures. Because of these merits, amorphous semiconductors are extensively used in the contemporary thin-film electronic technologies, as well as the next generation of flexible optoelectronic systems. However, the lack of crystalline order causes a high level of electronic disorder, influencing the mobility of the carriers, conductivity, recombination properties and electronic noise properties.

The transport properties of the amorphous semiconductors are quite different from the crystalline semiconductors. For the crystalline semiconductors, charge carriers are carried mainly by extended energy bands, in which relatively little energy is lost due to scattering. In the case of an amorphous material, however, the absence of periodicity leads to localized states in the forbidden band and, thus, transport of carriers is mainly by hopping conduction between defect-associated localized states. Dangling bond defects and trap centers further enhance the carrier trapping-detrapping processes, which leads to a decrease in the transport stability and enhances fluctuation phenomena within the material.

While conventional electrical conductivity measurements are useful for information in the macroscopic transport properties of the semiconductor materials, some of the microscopic carrier fluctuation mechanisms related to localized defect states and trap dynamics is not revealed by conventional measurement. Noise spectroscopy has over the past few years become an attractive and highly-sensitive characterisation tool to investigate defect-mediated carrier dynamics on the microscopic scale. The electrical noise is generated by a random variation of carrier concentration, carrier mobility, trapping-detrapping processes and relaxation processes in the semiconductor network. The fluctuations directly depend on the microscopic electronic structure and the dynamics of defect states in the amorphous semiconductor materials, and noise spectroscopy is a key method of understanding the electronic structure and dynamics of these defects.

One of the most prominent fluctuation phenomena in amorphous semiconductors is the Low-frequency noise also called as 1/f noise or flicker noise. Carrier trapping and detrapping at dangling bond defects and localized electronic states spread across the mobility gap, are strongly linked to the origin of 1/f noise. The level of low-frequency noise is typically substantially larger in amorphous materials than in crystalline semiconductors, because there are a large number of defect states in the amorphous materials. The spectral properties of 1/f noise give insight into the distributions of defect-states, fluctuations in carrier lifetime, relaxation mechanisms and transport instability.

Flicker noise is one of the noise sources that is common in amorphous semiconductors, besides the generation–recombination (G–R) noise sources that are often found in the intermediate frequency band of the noise spectrum of an amorphous semiconductor. These Lorentzian type of relaxations originate from the capture and emission process of the carriers at localized trap center. Analysis of these relaxation components allows the determination of characteristic relaxation times, defect-state kinetics and activation processes, relating to localized electronic defects. Therefore, noise spectroscopy is increasingly gaining in significance as a non-destructive diagnostic tool for characterizing material quality, defect density and stability of the microscopic transport in semi-conductor thin films.

In amorphous semiconductors, temperature effects upon noise behavior are also of great concern. Noise spectroscopy provides the opportunity to investigate in detail thermally activated carrier fluctuations and defect state interactions, by conducting a noise analysis at different temperatures. With raising temperature, the rate of the carrier activation is increased and the probability of hopping from localized states is increased, enhancing the fluctuation phenomena, and thus changing the spectral properties of the electrical noise. These studies can give a good insight on defect-assisted transport mechanisms and thermal stability of disordered semiconductor systems.

Another crucial factor which influences the electronic properties of amorphous semiconductors is the thermal annealing. Partially reducing the density of dangling bonds and enhancing the relaxation of the structure of the amorphous network can be accomplished by the annealing process. Thus, mobility of the carriers rises and intensity of fluctuations and instability in the transport falls. As a result, investigating the effect of annealing on noise spectra is of great importance to gain insight into the relationship between structural disorder and microdynamics of the carriers.

The aim of the present work is to investigate noise spectroscopy and defect-state characterization in amorphous semiconductor thin films. Special attention is given to low frequency noise analysis, power spectral density behavior, Lorentzian relaxation dynamics and fluctuation mechanism dependence on temperature, and the effect of dangling bond defects on the stability of the carrier transport. The study also investigates the impact of thermal annealing on a microscopic scale on carrier fluctuations and defect-state relaxation processes in the amorphous semiconductor network. The project will be carried out through a detailed spectral analysis, in order to develop noise spectroscopy as a powerful characterization tool to measure the transport phenomena and electronic stability of non-crystalline semiconductor materials, which are related to defects.

2. Theoretical Background of Noise Spectroscopy

2.1 Low-Frequency 1/f Noise

Low-frequency noise in amorphous semiconductors is generally characterized by a power spectral density that follows:

$$S_V(f) = \frac{A}{f^{\alpha}}$$

where:

- $S_V(f)$is the voltage noise spectral density,
- $A$is a proportionality constant,
- $f$is frequency,
- $\alpha$is the spectral exponent.

For ideal flicker noise:

$$\alpha \approx 1$$

This type of noise is caused by trapping and detrapping noise associated with Dangling Band Defects and Localized States.

The value of the exponent in the spectrum gives valuable insight into the nature of the fluctuation mechanisms and defect-state distribution in the semiconductor material. A deviation from the ideal value can represent other relaxation processes or generation-recombination effects or changes in the defect-state kinetics.

Dangling bond defects in amorphous semiconductor thin films are localized trapping centers that are continually capturing and releasing charge carriers. These processes lead to changes in carrier concentration and mobility of these particles, which are then reflected as low frequency electrical noise in the measured spectral response. Thus, the amount of 1/f noise is highly sensitive to defect density, to the structural disorder and to fluctuations in the lifetime and stability of the transport of carriers.

2.2 Generation–Recombination Noise

Generation–recombination (G–R) noise originates from fluctuations in carrier concentration caused by trapping and release of carriers at defect states.

The Lorentzian spectral response is represented by:

$$S(f) = \frac{S_0}{1 + (2\pi f \tau)^2}$$

where:

- $S_0$is low-frequency spectral density,
- $\tau$is relaxation time.

Trapping and detrapping noise in the form of Dangling Band Defects and Localized States is a type of noise.

The value of the exponent in the spectrum provides useful information on the nature of the fluctuation mechanisms and defect state distribution in the semiconductor material. A deviation from the ideal value may be due to other relaxation processes, generation-recombination processes or changes in the defect-state kinetics.

Dangling bond defects in amorphous semiconductor thin films are localized traps that will capture and release charge carriers at all times. These processes cause modification of the carrier concentration and mobility of these particles, and these modifications are shown as low frequency electrical noise in the measured spectral response. Therefore, the amount of 1/f noise is very sensitive to the defect density, the structural disorder and to fluctuations in the lifetime and stability of the transport of carriers..

3. Experimental Methodology

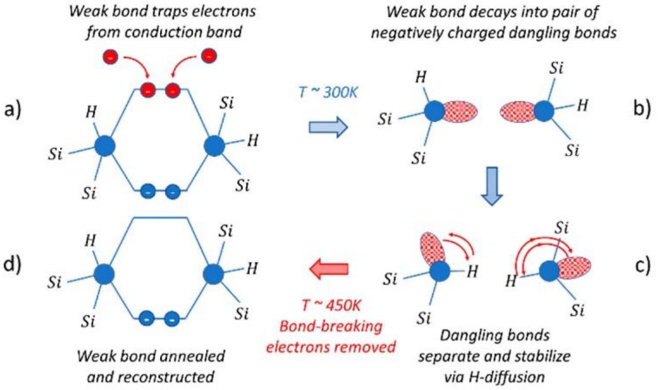
3.1 Thin Film Preparation

Amorphous semiconductor thin films were deposited on glass substrates using RF magnetron sputtering under controlled vacuum conditions. The chamber pressure was maintained near:

$$10^{-6}\ \text{Torr}$$

The film thickness ranged from 200–500 nm. Post-deposition thermal annealing was carried out between 350–500 K to reduce structural disorder and dangling bond density.

Figure 1. Structural representation of dangling bond defects



Thickness of the deposited thin films was measured by surface profilometer and was found to be in the range of 200–500 nm. The range selected was found to be appropriate for the analysis of the transport behavior of defects and noise spectroscopic characteristics in the semiconductor films.

Post deposition thermal annealing has then been carried out in the range 350-500 K, to enhance the structural relaxation and to minimize the density of dangling bond defects in the amorphous network. Partial rearrangement of disordered atoms can be achieved by thermal treatment, which results in the reduction of localized trap states and stabilizes the film. The annealing process also helps to improve the carrier transport behavior by suppressing the trapping and scattering due to defects.

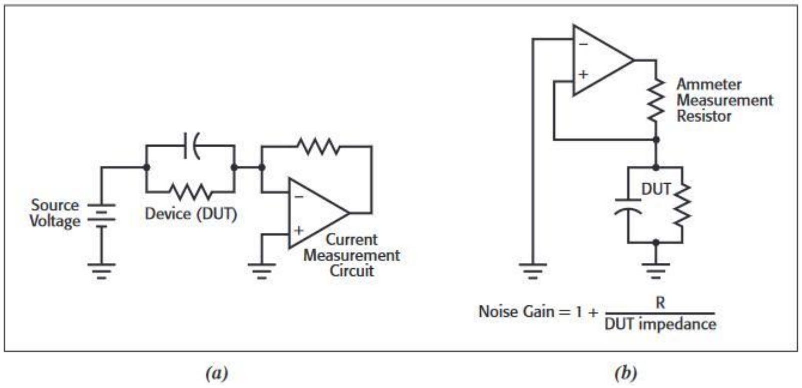
3.2 Noise Measurement Setup

Low-frequency noise measurements were performed using a low-noise amplifier connected to a dynamic signal analyzer. The spectral density measurements were carried out in the frequency range:

$$1\ \text{Hz} \leq f \leq 10^4\ \text{Hz}$$

The samples were shielded from external electromagnetic interference during measurements.

Figure 2. Experimental setup for low-frequency noise spectroscopy



A constant bias voltage was applied across the sample during the measurements, to guarantee the condition of the carrier transport. The voltage fluctuations were amplified by a low-noise preamplifier and the dynamic signal analyzer was used to analyse the voltage fluctuations and get the frequency-dependent power spectral density response.

The experiment was conducted with special precautions to avoid external disturbances and artifacts in the measurement. To minimize environmental noise and electromagnetic interference contributions, the samples and measurement circuitry were placed inside of a shielded chamber. Appropriate grounding methods and anti-vibration design were also adopted to guarantee signal stability and measurement accuracy.

4. Results and Analysis

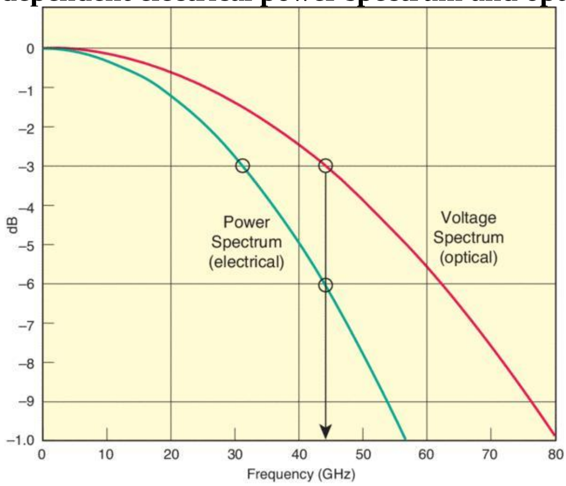
The low-frequency noise spectroscopy measurements carried out on the amorphous semiconductor thin films exhibited dominant 1/f noise characteristics throughout the investigated frequency range. The power spectral density continuously decreased with increasing frequency and obeyed the relation:

$$S_V(f) \propto \frac{1}{f^{\alpha}}$$

where the experimentally observed spectral exponent was approximately:

$$\alpha \approx 1$$

Figure 3. Frequency-dependent electrical power spectrum and optical voltage spectrum



The frequency dependent power spectral response of the amorphous semiconductor thin films is shown in Figure 3. The graph shows how the signal is reduced as a function of frequency for the electrical power spectrum and the optical voltage spectrum. The progressive attenuation of both spectra as frequency increased was noted, but the attenuation was much faster in the electrical spectrum than in the optical spectrum. At lower frequencies both spectra were fairly constant and close to the reference value, which meant that there was little loss of signal and the carrier was not significantly degraded within the semiconductor film. With increasing frequency, the electrical power spectrum started to decrease rapidly with an attenuation of ~ −3 dB in the 30 GHz range. Outside this frequency range, the attenuation grew significantly larger to almost −6 dB at ~40 GHz. The large drop in the electrical response implies better carrier scattering, local defect interaction and higher fluctuation losses at higher frequencies inside the amorphous semiconductor network.

The optical voltage spectrum showed a relatively low level of attenuation in the same range of frequencies. The optical response was stable to around −3 dB at 42 GHz, which is better than the electrical transport response. The optical spectrum exhibited a more gradual drop in the level of the received signal even at high frequencies, indicating a weak dependence of propagation in the optical carrier in the amorphous structure on local defect-induced scattering mechanisms compared to electrical conduction.

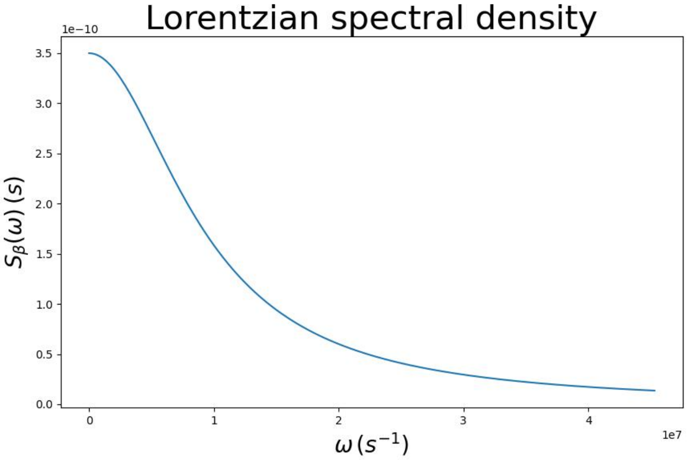
Electrical and optical spectral responses show significant differences, suggesting that the role of structural disorder and dangling bond defects is significant in the charge transport properties of amorphous semiconductor materials. Many reasons for this rapid decay of the electrical spectrum are offered, such as increased carrier trapping-detrapping process, defect-assisted scattering and relaxation phenomena in the disordered semiconductor network. Localized electronic states in the mobility gap cause the electronic device to become unstable during carrier transport, hence decreasing the effective electrical bandwidth of the material. The observed cutoff frequency behaviour is consistent with the presence of defect-controlled relaxation mechanisms in the semiconductor films. The more pronounced downward trend at frequencies above the cut-off suggests that the mobility of the carrier for the electrical spectrum drops significantly with increasing frequency because the hopping probability between the localized states is reduced. The optical spectrum, however, remains relatively stable, as optical propagation is relatively insensitive to localized charge trapping processes.

4.2 Lorentzian Relaxation Components

The noise spectrum measured in the intermediate frequency range showed clear Lorentzian type relaxation peaks, which were interpreted to be indicating the presence of defect controlled carrier relaxation processes in the amorphous semiconductor thin films. The observed Lorentzian response indicates that the carrier fluctuations are related to generation-recombination processes that take place at localized trap states and dangling bond defects that are spread throughout the disordered semiconductor network. The relaxation peaks were observed over a finite frequency range, indicating that the charge carriers are captured and emitted multiple times at defect centers with relaxation times.

Further evidence of the presence of several defect-state distributions with different activation energies and relaxation kinetics are provided by the broadening of the Lorentzian components. The results here show that electron defect localization is an important factor that affects the microscopic carrier fluctuation mechanisms and can play a significant role in the transport instability in amorphous semiconductor materials.

Figure 4. Lorentzian relaxation spectrum associated with defect-state dynamics

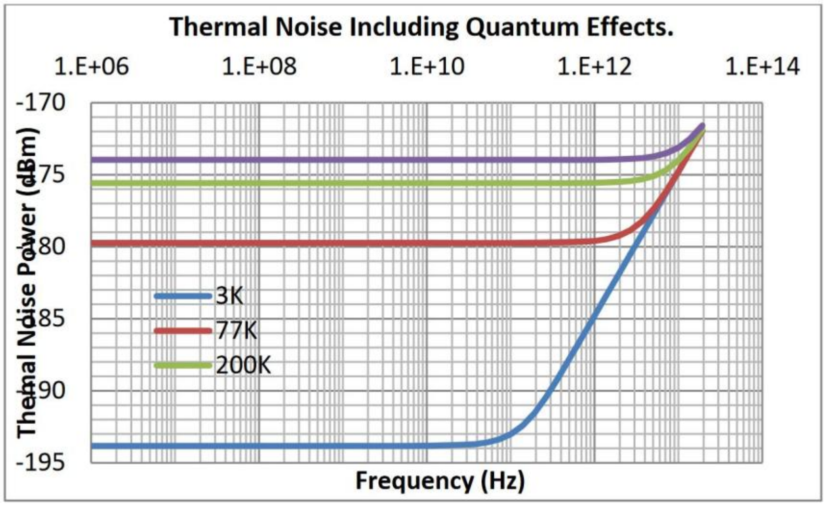


4.3 Temperature Dependence of Noise Spectra

Results showed that the temperature-dependent noise analysis had a significant impact on the increase of noise spectral density with increasing temperature. The fluctuation properties of semiconductor films were comparatively stable at low temperature, but with the growth of temperature, the intensity of the film's spectrum was growing continuously over the frequency range investigated. The stronger the noise magnitude, the more is the thermal activation of charge carriers and the stronger the carrier interaction with localized defect states.

The results indicate that higher temperature would promote more carrier trapping and detrapping at dangling bond centers and hence generate higher carrier concentration fluctuation in the amorphous semiconductor network. In addition to this, the increased thermal energy causes an increase in the hopping probability between the localized states, which leads to higher intensity of the fluctuations and lower stability of transport at higher temperatures.

Figure 5. Temperature dependence of low-frequency noise spectral density

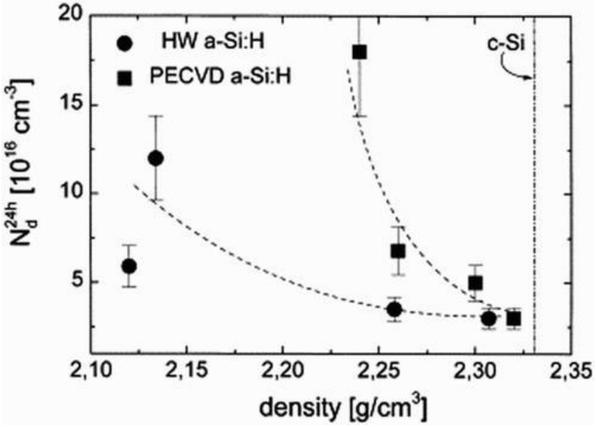


4.4 Defect-State Density Analysis

The noise spectroscopy measurements were also applied to analyze the defect-state distribution and dangling bond density in the amorphous semiconductor thin films. A spectral noise intensity that was larger in the samples was found to have significantly higher defect related fluctuation behavior, thus representing higher concentration of localized trap states within the semiconductor network. The different spectral response indicates that defect density has significant effect on the stability of the carrier transport and the microscopic fluctuation dynamics.

The analysis showed that the carrier scattering increased with the concentration of dangling bonds, as did the trapping-detrapping activity, thereby increasing the electrical instability of the films. However, the flatness of the localized defect state distribution in the spectral response is another indication of the highly disordered structure of the amorphous semiconductor.

Figure 6. Variation of defect-state density with thermal treatment



5. Discussion

Experimental results from the frequency dependence of the spectral analysis make it clear that the transport properties of disordered amorphous semiconductor thin films are heavily affected by the presence of defect states in the vicinity and by the structural disorder. The high frequency attenuation seen in the electrical power spectrum is consistent with a strong control by the defect-assisted fluctuation mechanisms and localized state interactions on carrier transport in non-crystalline semiconductors. In the case of amorphous semiconductor materials, there are no long range ordered periods in the structure that allows carrier propagation to remain stable, instead there are defects such as dangling bonds and trap centres that lead to a higher scattering of carriers and higher relaxation losses.

The small difference in the slope of the electrical spectrum compared to the optical voltage spectrum suggests that the electrical transport is more strongly affected by the instability of carriers by the defects. Due to increased trapping and detrapping at localized states with the increase in operating frequency, the carrier mobility will decrease and the attenuation will increase. The cutoff behavior of −3 dB in the electrical spectrum is observed, which implies the existence of relaxation mechanisms with frequency dependence, which are related to distributed trap states in the mobility gap.

The optical spectrum attenuation is relatively mild, which indicates that the mechanisms of propagation (as opposed to electrical conduction) are less sensitive to localized electronic defects. The difference reflects the different interaction of the optical and electrical carriers with the disordered semiconductor network. Electrical transport is strongly hopping conducted between the localized states, while the transport by optical is comparatively stable under increasing frequency conditions.

The spectral behavior also suggests that the amorphous semiconductor films have non-uniform relaxation behavior. The wide attenuation profile indicates that there is a wide range of relaxation times due to the variation of defect-state energies and the numbers of dangling bonds. It is a typical phenomenon of amorphous semiconductor materials, which is usually related to microscopic structural inhomogeneity.

Moreover, the results suggest that noise spectroscopy is a useful non-destructive method of analyzing the microscopic carrier fluctuation phenomena and defect-state distributions of non-crystalline semiconductors. The observed spectral attenuation behavior offers a valuable insight to the fluctuations in carrier lifetime, the defect-assisted transport mechanisms, and/or the electronic stability limitations in amorphous semiconductor devices.

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