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Laplace deep level transient spectroscopy study of intrinsic hydrogenated amorphous silicon

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ABSTRACT

Laplace deep level transient spectroscopy (LDLTS) measurements have been performed on undoped hydrogenated amorphous silicon samples. The LDLTS spectra of annealed and illuminated samples measured at wide range of temperatures show four fully resolved peaks labeled P1, P2, P3, and P4. For annealed samples, only the emission rate corresponding to P1 (the low emission rate one) increases slowly with temperature while all other emission rates are independent of temperature. These peaks were attributed to relaxation process associated with thermal transitions between different charge states of dangling bonds. Contrary to the annealed samples in the fully illuminated samples, all the emission rates corresponding to the LDLTS peaks are independent of temperature but follow, approximately, the same relaxation behavior. It was found that all these defects relaxation follow a power-law dependence of the emission times with the filling pulse duration. Our results don't show any new supplement peaks caused by light soaking of the samples. The light soaking effect was restricted to some changes in the relaxation process and can be readily explained by Adler mechanism.

1. Introduction

Defects in the energy gap of hydrogenated amorphous silicon (a-Si:H) have been investigated extensively in the past decades due to their role in controlling the electronic properties of this material. However, the origin and the nature of these states are still unknown. One of the major problems is the broad distribution of the defect states in the gap. The non-discrete nature of states in amorphous materials makes it difficult to experimentally resolve these states and hence clearly identify the corresponding defects. Different spectroscopic methods were used trying to identify the different defects in the gap of this material. Deep level transient spectroscopy (DLTS) has been used early in n-doped material [1,2]. The DLTS spectrum shows one large band peaked at 0.9 eV in the gap. In addition, charge DLTS (Q-DLTS) is used to detect the defects in undoped material [3]. Effectively, using Q-DLTS method, Nadazdy et al. [3] have performed a detailed study on the MIS structure of undoped a-Si:H samples deposited on the c-Si substrate. By annealing the samples under different bias voltages (then shifting the Fermi level) they identified, in the Q-DLTS spectra of the sample, three peaks at about 320 K, 390 K and 430 K with activation energies of 0.63, 0.82, and 1.25 eV respectively. Moreover, measurements of the capacitance and conductance were performed on Schottky structures in the quasi-stationary regime as a function of frequency and temperature [1,4–6]. Furthermore, the detailed study using different capacitance techniques performed on undoped a-Si:H showed more than one kind of defects [7,8].

It is well known that the dangling-bond (D) is the dominant deep defect in the mobility gap of a-Si:H. All the observations cited above were attributed to carrier transitions between different charge states of this defect. Depending on the position of the Fermi level (E_F), the D defect may be in three different charge states. One electron in the dangling-bond orbital makes the defect neutral (D^0). Two or zero electrons make it charged negative (D^-) or positive (D^+) respectively. By capturing electron or hole D can convert between these different charge states. Using junction-capacitance methods, Cohen et al. [9] reported relaxation process associated with electronic transition from D defect in n-type a-Si:H. They found that an electron's thermal release rate is inversely proportional to its residence time in the defect. This release time is equal to the filling pulse duration (t_p). In addition the decays of the trapped charge are virtually independent of temperature. Similar results were obtained in p-type a-Si:H [10]. Here again a temperature-independent emission time scales linearly with t_p, and the emission time decay follows the power law $t^{-\alpha}$ with $\alpha \sim 0.35$. Recently, the junction-capacitance method was also used for undoped material [11] and a different behavior from that observed in doped material has been reported.

Branz and Schiff [12] calculated D-defect relaxation energies and were able to explain the energy scale determined by capacitance methods. They found that the transition energies depend on the configurational dangling-bond. The levels of the fully relaxed defect correspond to transition without bond angle change, and the relaxation before the system reached a final state that depends on the configuration of the dangling-bond (Q). Branz and Schiff [12] proposed that dangling-bond relaxation is the movement of the dangling-bond from

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one of these configurations to another with accompanying changes in bond angles. Branz et al. [12–14] proposed a possible physical picture for the relaxation observed in n-type and p-type a-Si:H [9,10]. Upon trapping a charge carrier on a neutral dangling-bond during filling pulse, the threefold coordinated Si atom starts to change its bond angles. This change in the bond angle forces movement of the neighboring atoms to different positions. Considerable stress build-up around the charged dangling-bond. If the dangling-bond retains its charge long enough, a final step, involving a coordinated movement of many atoms can release the strain energy and transfer the system into different stable or metastable state. If the filling pulse duration is not long enough for this final step to occur, the stored energy permits a motion of some atoms back to the position they occupied before the filling pulse and the dangling-bond can move up in energy until the charge is thermally emitted. The limiting feature for the emission is therefore not the thermal emission time, but the motion of atomic position. Fedders and Branz [15] model this movement of atoms as a one-dimension walk in the configuration space of atomic position.

The capacitance techniques, cited above, have an important handicap that limits their capacity to give a detailed picture on the different defect distributions. This handicap is the bad spectral resolution in amorphous material, like in a-Si:H, where the spectrum shows a large band and hence it is hard to determine the different defects contributing to this band. Even if one records the entire transient and fits the transient curves with the appropriate functions [9–11], we will be limited by the number of functions (number of different kinds of defects) used in the fits. In other words, this method is adequate in the case, that only one or two kinds of defects among transient curve. However, in the case of the existence of more than two functions, reliable fit is more difficult because the invoked fit parameters become large. In the course of searching for better resolution to resolve subcomponent peaks with close emission times, it was found that a high resolution DLTS can be obtained by the application of inverse Laplace transform on the capacitance transient signal necessarily with high signal to noise ratio (SNR). A review of the so-called Laplace deep-level transient spectroscopy (LDLTS) applied to capacitance transient, which is due to point defect in semiconductors, was presented by Dobaczewski et al. [16]. This method provides a high resolution regarding the conventional DLTS but it is sensitive to the SNR [16]. It was possible to resolve many defect substructures in InP [17] and silicon [18,19] by using good systems allowing the averaging of the transient signal up to 1000 times.

In this paper, we present a detailed study of undoped amorphous silicon using LDLTS technique for annealed and fully illuminated samples. To my knowledge, this is the first use of this technique in the study of amorphous silicon material. Contrary to the results obtained by other capacitance techniques, our results don't show any thermal transitions but show four athermal emission rates due to relaxation process. The relaxation process of these emission rates is similar to the relaxation process observed in n-type and p-type a-Si:H. The origin of this relaxation process and the effect of light soaking on this relaxation will be discussed.

2. Experimental details

The films studied in this paper were deposited by conventional RF Plasma-Enhanced Chemical Vapor Deposition at 250 °C and deposition rates of 0.8–1 Å/s. Schottky diode samples were formed on films deposited on SnO_2 (ASAHI) covered Corning glass substrates. Phosphorous doped (n^+) a-Si:H with a thickness of about 20 nm was used to form the ohmic contact with the substrate. Palladium contacts with typical thickness of 50 nm and diameter of 1 or 2 mm were used as rectifying Schottky contacts. The capacitance transient measurements were performed using SRS-SR830 Lock-in analyzer (in frequency range 1 mHz to 100 kHz). The major difference from the standard DLTS set-up is the use of low-frequency (1 mHz–100 kHz) capacitance meter (SRS-SR830 Lock-in analyzer). A low frequency measurement is necessary to make the dielectric response turn-on at a temperature low enough to observe g(E) over an appreciable fraction of the gap [1]. We found that the best choice to have low temperature turn-on dielectric response and a good signal to noise ratio is 5 kHz, so all the capacitance transients presented in this work were performed at this measurement frequency with an amplitude of 30 mV r.m.s. The Lock-in analyzer signal is amplified and filtered using a low-noise high-sensitivity current amplifier SR570 and then digitalized using digital oscilloscope TekTronix-TDS3054C providing a signal averaging up to 512 times. The averaging function is essential to enhance the SNR and consequently obtain a SNR as high as 1000. Moreover, a computer acquisition program is written to receive the digitalized transient waveforms and then store them sequentially according to the sample temperature. The sample temperature is controlled by a closed cycle helium cryostat (Janis CQ-2650) enabling temperature adjustment in the range of 10 to 500 K with precision of 0.1 K. This set-up can provide digitalized transient signal waveforms with up to 10,000 points per transient curve. The inverse Laplace transform calculations were performed using commercial Laplace program [16]. The errors in the determination of the peak positions were calculated by recording the transient, at a given temperature, five times and calculating the LDLTS spectra. The peak position in the data is then the average value. Light soaking of the samples was performed for 36 hours using Arc-Xenon lamp at power about 1 W/cm^2.

3. Experimental results

The capacitance transients are recorded using −3 V reverse bias pulsed to zero (pulse amplitude 3 V) and pulse duration varying from 10 μs to 10 s. Fig. 1 compares the DLTS and LDLTS spectra, where the power resolution of LDLTS is clearly demonstrated. However, faced

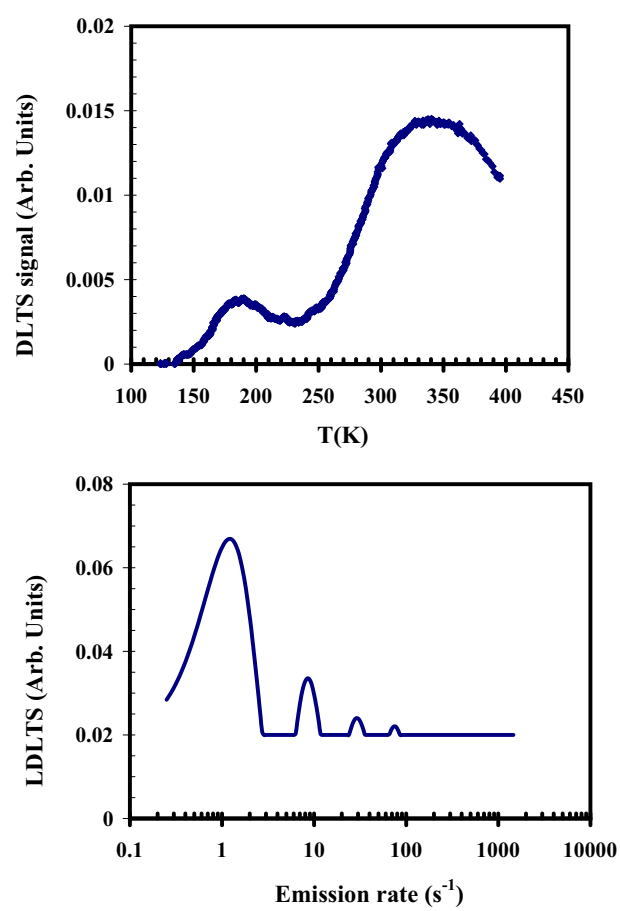

Fig. 1. Comparison between the DLTS spectrum and the LDLTS spectrum recorded at T = 350 K, the temperature of the DLTS peak at maximum for 1 ms of pulse duration.