Effects of secondary laser illumination during the transient measurement in optical and electrical deep level transient spectroscopy

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(Received 29 April 1991; accepted for publication 21 July 1991)

To separate the majority and minority carriers in the deep level transient spectroscopy (DLTS), the transient is usually measured in the dark. However, under some circumstances, the transient measurement should be performed under illumination. In these cases, the effects introduced by the illumination become a concern. In this letter, effects of secondary laser illumination on samples of hydrogenated amorphous silicon (*a*-Si:H) during the transient measurement in optical and electrical DLTS are reported. The experimental results show that background illumination decreases the time constant of the transient but it is unlikely to create new gap states during the short time period.

Deep level transient spectroscopy[1,2] (DLTS) is a useful tool in determining the thermal emission properties of deep levels of impurities and defects in semiconductors. The energy levels and free-carrier-capture cross sections of these deep level defects are obtained by measuring the transients of electrical parameters, such as junction capacitance,[1,2] current,[3] or charge[4] of a reverse biased *p*–*n* junction or Schottky diode, following an electrical or optical pulse during a temperature scan. To separate the majority and minority carriers in the measurement, the transients are usually measured in the dark. However, in the new contactless optical reflectance transient measurement, the transient should be performed under illumination.[5,6] In these cases, the effects introduced by the illumination become a concern. In this letter, we report the effects of secondary (background) laser illumination on the DLTS transients using conventional optical and electrical pulsed excitation.

A sample of PH_3 doped *n*-type *a*-Si:H film grown onto n^+ Si substrate was used in the experiment. For the measurement of DLTS, a Schottky diode structure was fabricated by evaporating Au/Cr onto the *a*-Si:H film. A DLTS system shown in Fig. 1 was employed. Such an experimental system allows use of various operation modes, such as conventional electrical DLTS (EDLTS) and optical DLTS (ODLTS) and some new all optical operation modes[6,7] with an optical pump pulse as a excitation source and measuring the optical probe reflectance transients[8] or the infrared radiation transients.[9] Figure 2 represents the experimental sequences corresponding to the two conventional EDLTS and ODLTS modes: time dependence of different excitations, two different conditions during the transient measurements—dark condition and background illumination, and the relevant capacitance transients. To clarify the effects of background illumination during the transient measurement, we measured the capacitance transients under a cw laser light illumination and compared it with the results measured under the dark condition,

Two capacitance transients measured in the dark and under illumination at room temperature during ODLTS are shown in Fig. 3. Clearly, the base line of the transient changed due to the background illumination. This reflects the fact that the deep level occupancy can be changed by the optically induced emission of carriers, leading to a change of the capacitance of the Schottky diode. An increase in the free carrier population at the junction due to the He–Ne laser beam is consistent with the increase in the total charge density in the neighborhood of junction. This would result in an increased value of the junction capacitance under constant bias conditions, in agreement with the trends in Fig. 3. Furthermore, it is clear from Fig. 3 that not only the base line but also the time constant of the

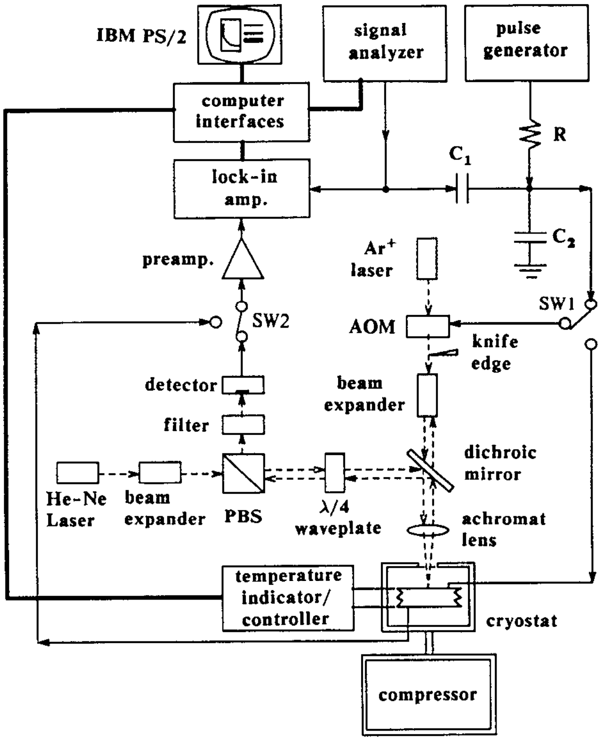

FIG. 1. Schematic of the experimental setup used for deep level transient spectroscopy (DLTS). The system allows various excitation modes to be carried out by properly switching two switches (SW1 and SW2). Dashed lines represent the optical signal paths, solid lines represent the electrical signal paths and the thick solid lines represent the computer interfaces. C_1, C_2: capacitors; AOM: acousto-optic modulator; PBS: polarizing beam splitter.

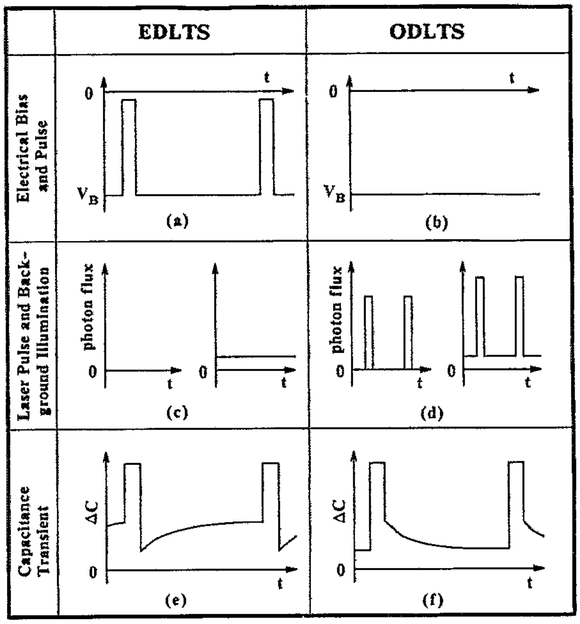

FIG. 2. Experimental sequences involved in the EDLTS and ODLTS experiments. EDLTS: (a) electrical excitation and reverse bias. (c) Two different illumination conditions. (e) Relevant capacitance transient. ODLTS: (b) Electrical reverse bias. (d) Optical excitation and two different illumination conditions. (f) Relevant capacitance transient.

actual transients changed due to the illumination. To quantify this point, Fig. 4 shows the rate-window scanned DLTS spectra[10] that is produced from Fig. 3.

The time constant τ, which is the inverse of the carrier thermal emission rate for a particular trap level of depth E in an n-type material, is given by[1]

$$\tau^{-1}=\nu_0 \exp(-E/kT), \tag{1}$$

where the emission frequency

$$\nu_0=\begin{cases}\sigma_n\langle v_n\rangle N_c & \text{for majority carriers}\\ \sigma_p\langle v_p\rangle N_v & \text{for minority carriers}\end{cases}. \tag{2}$$

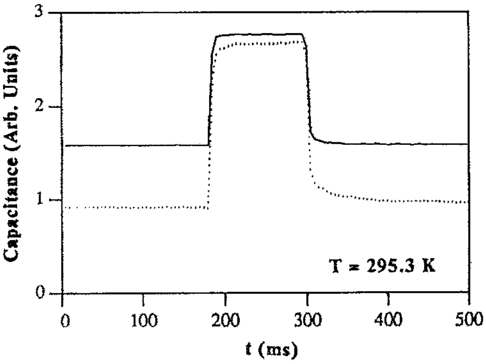

FIG. 3. Actual capacitance transients for ODLTS. Solid line represents the capacitance transient measured under background illumination with a 2 mW 632.8 nm He–Ne laser beam collinear with the pump Ar$^+$ laser beam and dotted line represents the transient measured in the dark.

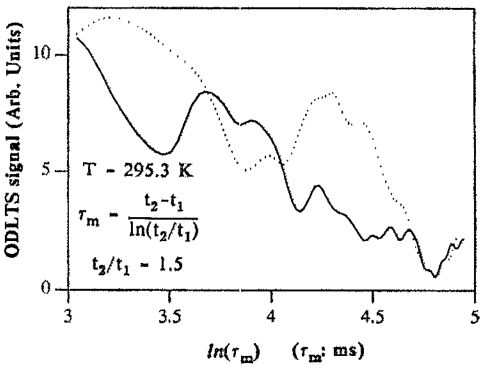

FIG. 4. Rate-window scanned DLTS spectra of Fig. 3. Solid and dashed lines correspond to those of Fig. 3. τ_m is the DLTS rate window. Quantity of $\ln(\tau_m)$ shifted -0.57 because of the background illumination.

The time constant τ varies experimentally when the sample temperature is scanned during the experiment, while the instrumental rate window is held fixed in order to produce a DLTS spectrum. Instead, in Fig. 4 we hold the sample temperature constant and scan the rate-window parameters with the ratio t_2/t_1 remaining constant ($t_2/t_1=1.5$). By doing so, the DLTS spectrum reaches the maximum when the instrumental rate window matches the time constant of the capacitance transient. The horizontal axis in Fig. 4, which is chosen as $\ln(\tau_m)$, corresponds to the energy scale given by

$$E=kT\ln(\nu_0\tau_m) \tag{3}$$

which is determined from the inverse of Eq. (1).

The actual DLTS spectra in Fig. 4 are proportional to the density of gap states $g(E)^1$ in a-Si:H sample. From Eq. (3), the energy is a logarithmic function of rate window at constant temperature. Any new gap state, which could be generated by long-time interband optical exposure as suggested by Staebler and Wronski,[11] would be expected to change the density of gap states, therefore to change the shape of rate window scanned DLTS spectra. However, besides a shift in x axis (energy scale), the shapes of two ODLTS spectra in Fig. 4 remain qualitatively similar. This leads to the conclusion that the possibility of new gap state generation by illumination is small in this case.

According to Eq. (3), this curve shift occurring in Fig. 4 can be caused by a change of ν_0. Differentiating Eq. (3), one obtains

$$\Delta E=kT(\Delta\ln\nu_0+\Delta\ln\tau_m). \tag{4}$$

For any physical junction, the energy level scanned should remain the same under variable illumination ($\Delta E=0$). The shift in Fig. 4 [$\Delta\ln(\tau_m)$] could thus be the result of a change in $\Delta\ln(\nu_0)$. For example, $\Delta\ln(\tau_m) = -0.57$ in Fig. 4 suggests that ν_0 increased 1.77 times under the He–Ne laser illumination. Eq. (2) now suggests that the light has increased either the effective density of states at valence band edge, N_v, or the hole capture cross section of recombination centers σ_p but did not create new energy states.

The capacitance transients are also measured in the dark and under various illumination conditions in the EDLTS mode. The Ar$^+$ laser illumination increased the base line and shortened the time constant of the transient:

the stronger the intensity of the light, the shorter the time constant of the transient. Applying the same analysis as above, one can reach similar results as in ODLTS, that the background illumination has increased either the effective density of states at conduction band edge N_c or the electron capture cross section σ_n. Although more experimental work is required to sort out which component in v_0 is responsible for the observed effects, it appears likely that the carrier capture cross sections are affected through the dependence of the transition rate on the intensity of the radiation field.[12,13]

In conclusion, we have demonstrated for the first time the effects of background illumination during the transient measurement in DLTS. The experimental results show that the illumination will decrease the time constant of the transient but it is unlikely to create new gap states during the short time period. This suggests that as long as we taken into account the time-constant shift due to the background illumination when we reconstruct the energy levels of the defects, we can use a cw probe laser beam to measure the transient reflectance signal instead of the conventional capacitance transient. This is expected to provide a noncontact, nondestructive means of evaluating the thermal and optical emission properties of semiconductors.

The authors are grateful to Professor S. Zukotynski of University of Toronto for providing the samples used in this work. Support for this work by the Natural Sciences and Engineering Research Council of Canada (NSERC), as well as by the Ontario Laser and Lightwave Research Center (OLLRC) is gratefully acknowledged.

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