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DLTS and C(t) transient study of defects induced by neutron radiation in MOS structures of CCD technology

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Abstract: *The aim of this paper is to study neutron irradiation effects on PMOS capacitors and NMOSFETs transistors. The characterization of induced defects was made by capacitance transients C(t) measurements, DLTS spectroscopy, and optical DLTS (ODLTS). DLTS spectra present three peaks (1, 2, and 3) due to deep levels created in the semiconductor and two peaks (4 and 5) due to minority carrier generation. Levels 1 and 2 are reported in literature and it was suggested that the level 2 may be due to the divacancy. Two other minority carrier traps have been observed on ODLTS spectra after irradiation. This can explain the decrease of the minority carrier generation lifetime observed in capacitance transients measurements.*

Introduction: Neutron irradiation effect on silicon was largely studied using several techniques. It was noted by Tokuda and Usami [1][2] that neutron irradiation induces two deep levels in the gap of P-silicon. Deep Level Transient Spectroscopy (DLTS)[3] enables us to determine the signature of majority and minority carrier traps electrically active in the band gap[4][5][6].

Induced recombination centers will modify minority carrier generation parameters such as the effective generation lifetime τ'_g and the effective surface recombination velocity S_{eff}, which may introduce a variation in a CCD structure dark current. Capacitance transients show the evolution of these parameters with irradiation. Results of characterization by DLTS and pulsed MOS capacitor methods[7] for MOS structures after neutron irradiation are presented in this work.

It is shown that five deep levels are created in the semiconductor. Three of them are majority carrier traps and two are minority carrier traps. Two peaks related to the minority carrier generation are also detected by DLTS spectroscopy and the generation parameters have been determined using the capacitance transients C(t) methods.

Experimental Details: Experiments were conducted on n-MOS technology test devices manufactured by THOMSON CSF SEMICONDUCTEURS SPECIFIQUES in a CCD technology. The effective doping in the silicon semiconductor was $5\times10^{14}cm^{-3}$. Two different oxide thicknesses are available, T_1 = 500 and T_2 = 850Å. The PMOS capacitors have gate area of (240× 650μm²). Gate area of the transistors is (400×400μm²). The characterized samples were distributed into two lots and subjected thereafter, without no bias and during eight hours, to fluences of 5×10^{13} neutrons cm^{-2} and 10^{14} neutrons cm^{-2} respectively. The defects were analyzed by deep level transient spectroscopy (DLTS). In the DLTS technique, the MOS structure is repetitively electrically pulsed from depletion to accumulation (introducing majority carrier into depletion region). Capacitance transients due to emission of majority carriers from defects can be observed. In the ODLTS technique, the MOS structure is repetitively pulsed with an optical excitation in order to characterize minority carrier traps. As the temperature is scanned a peak is observed in the spectrum when the emission rate of a particular defect equals the selected "emission rate window"[3]. The DLTS and ODLTS measurements were made using a DLS 82E lock-in spectrometer manufactured by Semilab Physics Laboratory, Hungary.

Capacitance transients observed at room temperature when the MOS structure relaxes from deep depletion to inversion are also studied to characterize the minority carrier generation parameters. The capacitance versus time measurements were performed with a capacitance meter HP 4280A.

Results and Discussion:

A. DLTS and ODLTS Characterization - Only one peak, which appears at high temperatures in the DLTS spectra of the studied structures, was detected (Figure 1). His evolution with the quiescent bias voltage guarantees that it is due to minority carrier generation[8]. This peak was reported to the carrier diffusion from the quasi-neutral region [9][10], since the Arrhenius plot of the peak gives activation energy of approximately 1.15eV, which is very close to the band gap of silicon. No bulk defects in the semiconductor were detected at low temperature.

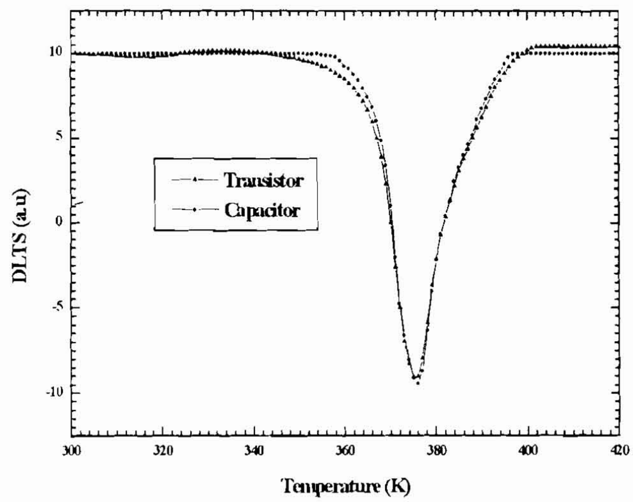

Figure 1. DLTS spectra obtained before irradiation

After irradiation, five peaks appear in the NMOSFETs spectra but only four appear in the PMOS spectra (Figure 1). Peaks 4 and 5 were always found in the temperature range 240-330K. These peaks were attributed to the generation of minority carriers because they are not present in DLTS spectra recorded on n^+p drain substrate junctions of transistors. Since peak number 4 does not appear in capacitors spectra (Figure 2), it was assumed to be due to the minority carrier injection from the drain and source of the transistors.

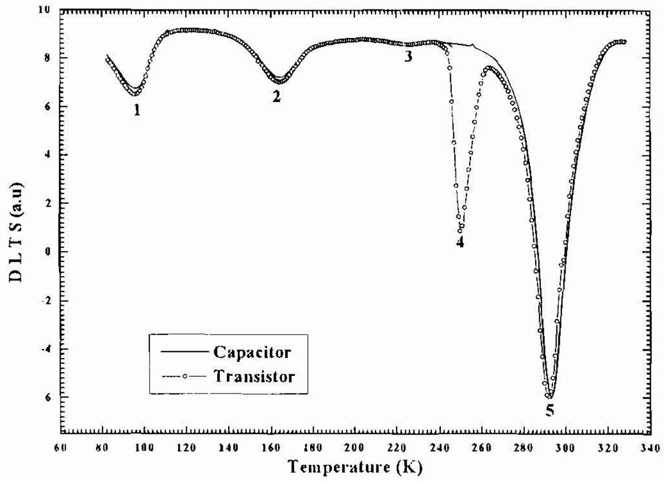

Figure 2: PMOS capacitors and NMOSFETs DLTS spectra obtained after neutron irradiation

Peak 5 seems to be of the same nature as the one observed on measured spectra before irradiation (same activation energy). The shift of this peak towards lower temperature after irradiation can be interpreted by a change in minority carrier generation parameters. The study of capacitance transients described in the paragraph B will show the evolution of these parameters with irradiation. The study of the peak positions according to the emission rate window by an Arrhenius analysis will allow the characterization of the related defects.

Figure 3. shows the Arrhenius plots for peaks number 1, 2, and 3. The energy levels of the defects 1, 2, and 3 were estimated to be $E_1 = E_v+0.18eV$, $E_2 = E_v+0.35eV$ and $E_3 = E_v+0.44eV$. The corresponding capture cross sections are: $\sigma_1=4.6\times10^{-16}cm^2$, $\sigma_2=4.9\times10^{-15}cm^2$ and $\sigma_3=3.5\times10^{-16}cm^2$, respectively.

Peak number 1 may correspond to the P-1 level mentioned by Tokuda and Usami [11][12]. No identification was made for this level. It is considered that peak number 2 corresponds to the P-2 level reported by Tokuda and Usami [11]. They concluded that this peak corresponds to the divacancy. Peak number 3 is not mentioned in literature, it may be due to the interface states created by neutron irradiation.

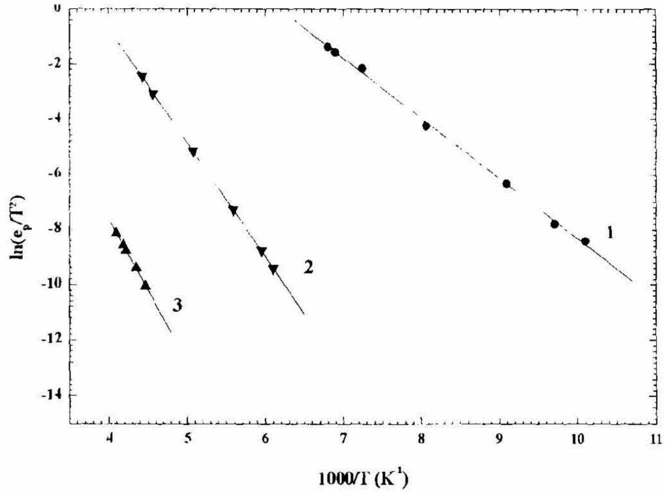

Figure 3: Arrhenius plots obtained for the peaks numbered 1, 2, and 3

Figure 4 shows a typical ODLTS spectrum measured after irradiation with an emission rate window of 2.17 s^{-1}.

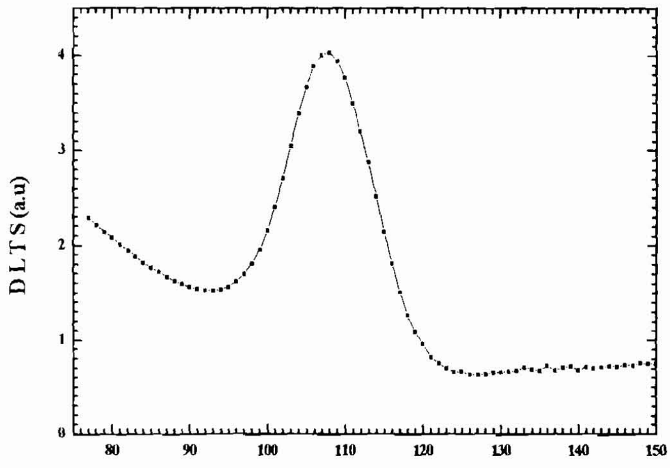

Figure 4: ODLTS spectrum obtained after neutron irradiation

The characterization of the peak by Arrhenius analysis revealed two slopes which can be interpreted by the presence of two defects.

We found two activation energy values: E_c-0.2eV and E_c-0.3eV. E_c-0.2eV is the same activation energy as level E_2 defect reported by Tokuda and Usami [13]. They related this defect to double minus charge state of the divacancy.

B. Capacitance Transients Characterization - In order to see how minority carrier generation in dark was affected by the detected defects, capacitance-time measurements (C(t)) were used [7][14]. These measurements consist in pulsing a MOS structure in deep depletion and monitoring the capacitance transient which reflects the carrier generation process[15].

Many methods based on C(t) transients measurements are used to determine the minority carrier generation parameters. The $1-\left(\frac{C_i}{C}\right)^2$ and Zerbst's methods are the most widely used techniques.

Zerbst's technique[7][14] has been used in such a way that a straight line is obtained, the slope of which gives the effective generation lifetime τ'_g and the intersection with the Y ordinate axis gives the effective surface recombination velocity S_{eff}. This later parameter is a function of the effective diffusion length L'_n and the space charge region surface generation velocity S_g[7]. One limitation of the Zerbst's analysis is the assumption that generation in the space charge region is the dominant process.

The $1-\left(\frac{C_i}{C}\right)^2$ method[7] , C_i being the initial capacitance, has been used to directly determine the effective diffusion length L'_n. This parameter is a function of diffusion length

L_n and surface generation velocity of the back contact S_c. The $1-\left(\frac{C_i}{C}\right)^2$ method is applicable when diffusion from the quasi-neutral region is the dominant mechanism of minority carrier generation. L'_n is related to L_n by a non linear equation [7][10][14] which can be simplified when the surface generation velocity of the back contact is negligible[7][10].

As mentioned in the DLTS study of non irradiated samples, only diffusion process contributes to the equilibrium establishment. This mechanism is characterized by the diffusion length L_n. This parameter has been calculated from the slope of the plot of $1-\left(\frac{C_i}{C}\right)^2$ versus time. An average value of 1200µm is been obtained

Generation process is found to be negligible in these structures because the Zerbst's plots give very high generation lifetimes. L_n has also been determined using Zerbst's plots by neglecting the surface generation velocity term. The values obtained by the two techniques are in good agreement (Table 1). This confirms that generation from the interface between oxide and semiconductor is negligible and the good shows quality of these MOS structures.

Table 1

Minority carrier generation parameters obtained before irradiation

		Before	After
Zerbst's method	τ'_g (µs)	****	1.7
	S_{eff} (cm s^{-1})	3 x10^{-5}	0.6
	L_n (mm)	1.2	1.7 x10^{-4}
$1-(C_i/C)^2$ method	L_n (mm)	1.2	1x10^{-4}

After irradiation, the storage time of the C(t) transients was strongly reduced. It becomes lower than one second which is very small compared to storage time before irradiation (more than two hours). The effective generation lifetime was determined from Zerbst's plots slopes. An average value of 1µs has been obtained. L_n was calculated using the two methods discussed above. The obtained values are different (Table 1). This is mainly due to the surface generation velocity S_g which cannot be neglected. Indeed, capacitance-voltage C(V) measurements showed that the surface state density is not negligible after irradiation.

Table 1 shows also the strong reduction in the diffusion length after irradiation. This is related to the decrease of the recombination lifetime velocity caused by new recombination centers created after irradiation and detected by DLTS measurements.

The effect of the oxide thickness, fluence of neutrons, kind of structures (capacitor or transistor) on C-t transients can not be yet clearly reported.

Conclusion: Neutron irradiation produced defects in P-type silicon have been studied by deep level transient spectroscopy (DLTS). DLTS spectra show five peaks after neutron irradiation. Two of them (number 1 and 2) are related, respectively to the P-1 and P-2 levels reported by Tokuda and Usami. Level P-2 is due to the divacancy. Peak 3 may correspond to interface states with a maximum of density around E_v+0.44eV. Peaks number 4 and 5 are related to minority carrier generation. Minority carrier traps have been also characterized by ODLTS. A dramatic decrease in minority carrier generation lifetime and diffusion length after neutron irradiation is found by capacitance transients analysis. This corroborates DLTS results. The operation of MOS structures in CCD devices is strongly affected by an increase in the dark current.

These results show well the interest and complementarity of DLTS and capacitance transients measurements to study defects produced by neutron irradiation in MOS structures.

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