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IDENTIFICATION OF THE CARBON ASSOCIATED RADIATION DAMAGE LEVELS IN SILICON

G. Ferenczi, C. A. Londos*, T. Pavelka and M. Somogyi
Research Institute for Technical Physics of the HAS
1325 Budapest, Ujpest 1., P.O. Box 76, Hungary

A. Mertens
Humboldt Universität, Sektion Physik, Bereich 06. Berlin, GDR

The dominant carbon related radiation damage centre in silicon was studied in detail. In contrast to previous studies the presence of two clearly distinguishable defects were established: one at $E_V+E_T = 0.370$ eV. $\sigma_p = 8\times10^{-18}$ cm^2 and assigned as the C_S-Si_I-C_S complex, and another one at $E_V+E_T = 0.344$ eV, $\sigma_p = 1.1\times10^{-16}$ cm^2 and assigned as the COV_2 complex. It is suggested that the concentration of the C_S-Si_I-C_S centre is indicative to the overall carbon concentration, hence the peak separation technique presented in this paper can be used to measure low - with IR absorption non-detectable - carbon concentrations in Silicon.

INTRODUCTION

The yield and properties of very large scale integration (VLSI) devices which are mainly fabricated on Czochralski (CZ) silicon wafers are significantly influenced by the behaviour of oxygen in the silicon substrates. It is well established [1,2] that the presence of carbon in the silicon lattice significantly influences the precipitation properties of oxygen acting as a nucleation site. It is argued [1] that low carbon concentration is favourable. The widely used IR absorption technique can not usually detect carbon concentrations below 1×10^{16} cm^{-3} on samples with standard wafer thickness. Alternative ways to detect low carbon concentrations would therefore be welcome.

Radiation damage levels are the best characterized defects in silicon, only a selection of the published results are referenced here [3-9]. It was shown that the most common defects introduced by irradiation are complexes involving carbon and oxygen beside the simple point defects. In the present work we intend to concentrate on a carbon related level usually reported with $E_V+E_T = 0.36$ eV, which forms around room temperature and anneals out around 400 ^oC. This defect was first described more than 20 years ago [10] but its identity is still subject to controversy, the candidates being: COV_2 or C_i-C_S (recently corrected as C_S-Si_I-C_S by [11]). The intention of the present paper is to resolve this long standing controversy and suggest a calibration procedure for determining the concentration of carbon in silicon using the properties of

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this defect.

EXPERIMENTAL

10-15 ohmcm B doped p-type silicon materials were used. Three groups of samples were selected:

	Float Zone (FZ)	Czochralski low C	Czochralski high C
N_{O_I} [cm^{-3}]	$<10^{16}$	$5x10^{17}$	$5x10^{17}$
N_{C_S} [cm^{-3}]	$<10^{16}$	$<10^{16}$	$5x10^{16}$

Table I.

Schottky contacts were prepared by A_g^+ implantation (30 keV, $3x10^{16}$ dose/cm^2) as described in [12].
Subsequently the samples were implanted with H^+ at 300 keV and at room temperature, using variing dose levels between ($4x10^9$-$6x10^{10}$) dose/cm^2. DLTS measurements were performed with a high sensitivity lock-in type spectrometer DLTS-82E, manufactured by Semitrap, Hungary.

RESULTS; DISCUSSION

Six radiation damage levels were observed in the majority carrier spectra, in the present work we concentrate only on the level, labelled as H_4 [13]. It was noted that the introduction rate of this defect is twice as high in $CZ_{high\ C}$ samples than that of the other levels. Detailed Isothermal Frequency-Scan [13] measurements were performed to determine the capture cross section of this level. Typical example is shown on Fig. 1. H_4 is produced as a recoil cascade

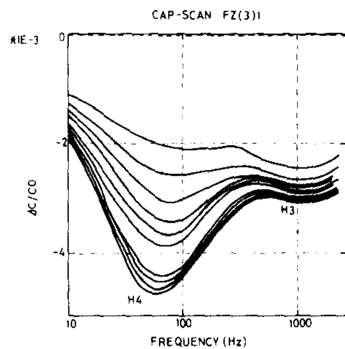

Figure 1/a
Series of capture cross section measurements in frequency scan mode at T = 200 K

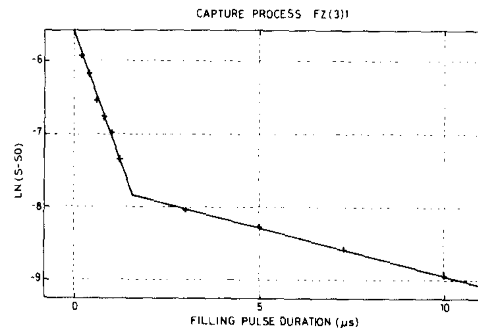

Figure 1/b
The corresponding evaluation of the two capture cross section

process by the A_g^+ implant, the maximum is centered at 180 nm, and by H^+ implant centered at 2.7 μm. Capture cross section measurement on the proton induced defect was performed selecting the amplitude of the reduced reverse bias pulse to reach a defect free part of the junction in order to eliminate the influence of the free carrier tail on the capture rate. Two clearly distinguishable capture rates were measured. The values of the capture cross

sections averaged over 8 samples (the accuracy of the individual measurements are better than 5 %):

$$\sigma_p \text{fast} = (1.1 \pm 0.1) \times 10^{-16} \text{ cm}^2$$

$$\sigma_p \text{slow} = (8 \pm 2) \times 10^{-18} \text{ cm}^2$$

The much lower value reported by [6] for the slow process is probably due to the influence of the edge layer effect.
The H_4 level induced by Ag^+ implantation contains only the slow component, the H_4 level induced by high dose H^+ implantation in the CZ_{lowC} samples contains only the fast component within measurement accuracy. The peak labelled as H_3 on Fig. 1/a. was not reported previously. This is mainly due to the superior energy resolution of the frequency scan technique. (To achieve equivalent energy resolution with temperature scan significant data points should be recorded at every 0.04 K). We believe that the large scatter - 0.33-0.38 eV - reported in the literature for the activation energy of H_4 [3-9] is partly due to the admixture of H_3. The capture cross section of H_3 is $\sigma_{pH_3} = 2.7 \times 10^{-16}$ cm^2. It is important to decide whether the different capture rates observed for H_4 originate from the same defect or we are dealing with two different species. Using the Differential DLTS [14] variant of the Isothermal Frequency-Scan DLTS we succeded to separate two levels. Two filling pulses, separated in time by half of the period lenghts, with equal amplitude but different duration were used. The first pulse was long enough to fill both states, the second pulse filled only the faster state, hence the residual signal contained information only about the slower state. Alternatively, using a single filling pulse, short enough to fill only the faster state, the activation energy of the fast state can be determined independently. The result is illustrated on Fig. 2. The measured activation energies (averaged over 8 samples, the accuracy of the measurement on a single sample is ±1 meV.):

$$(E_V+E_T)_{fast} = (0.344 \pm 0.006) \text{eV}$$

$$(E_V+E_T)_{slow} = (0.370 \pm 0.002) \text{eV}$$

For completness, the activation energy for H_3

$$(E_V+E_T)_{H_3} = 0.279 \text{ eV}$$

The unusual accuracy of the measurement data (capture cross section and activation energy) is due to the thermal equilibrium conditions achieved during frequency scan. As a conclusion it can be stated that the peak separation technique described previously allows the determination of the individual concentration of the two components as well.

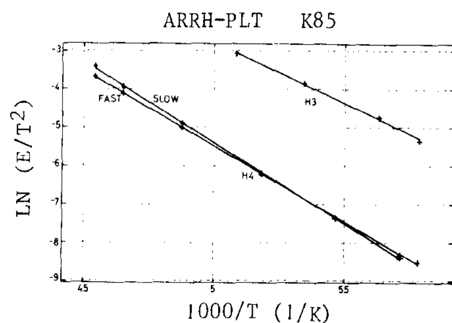

Figure 2
Arrhenius plots measured in frequency scan mode. The slow process was determined by the double pulse technique described in text

These types of measurements were performed on all proton induced H_4 peaks in the three different kind of materials as the function of proton dose. The dose dependence of the slow component of H_4 is illustrated on Fig. 3. It is clearly seen that the relative weight of the slow component increases with increasing dose in the FZ and CZ_{highC} samples but decreases in the CZ_{lowC} samples. Based on these results we propose to identify the fast component with the COV_2 complex [15] and the slow component with the C_S-Si_I-C_S [11,16] complex. Both defects form around room temperature via the mobile carbon interstitials [4]. It is assumed that the COV_2 complex forms when C_i interacts with the already

present VO compexes [6]. This reaction seems more favourable than the interaction with another carbon atom. The concentration of VO is, however, between $(10^{13}-10^{14})$ cm^{-3} in the samples investigated here while the carbon concentration is between $(10^{15}-5x10^{16})$ cm^{-3}, hence the formation of the $C_S-Si_I-C_S$ complex becomes more preferable at higher doses. The only notable exception is the CZ_{LowC} sample at $5x10^{10}$ proton/cm^2 where $N_O/N_C \sim 10^2$ as compared to other samples where $N_O/N_C \sim 10^1$, hence this data also supports our identification. Finally the H_4 peak produced by recoil ions due to the $3x10^{16}$ Ag^+/cm^3 implantation contains only the slow component. (The relative magnitude of the two components should be within two orders of magnitude to make it separable with the experimental technique used in the present work.) We assume that the H_4 concentration measured near the M-S interface is the saturation value of $C_S-Si_I-C_S$:

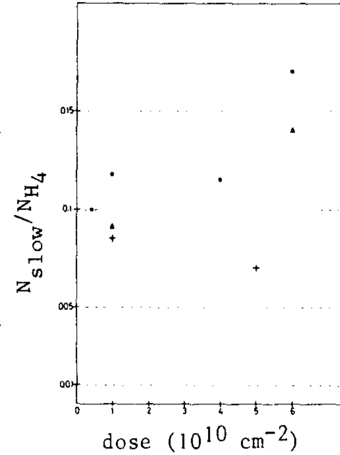

Figure 3
The dose dependence of the relative magnitude of the slow process:
FZ•, CZ_{lowC} +, CZ_{highC} ▲.

	FZ	CZ_{lowC}	CZ_{highC}
N_{H_4} $[Ag^+]$	$1x10^{15}$ cm^{-3}	$8x10^{14}$ cm^{-3}	$5x10^{15}$ cm^{-3}

Table II.

From this assumption follows, that at intermediate doses

$$N_{C_S-Si_I-C_S} = N_{sat}(1-e^{-x/a}) \quad (1)$$

or in linear approximation

$$\frac{N_{C_S-Si_I-C_S}}{N_{sat}} = \frac{x}{a} \quad (2)$$

where x is the proton dose/cm^2.

To test the model the measured magnitudes of the slow components were plotted on Fig. 4. according to equation 2. The agreement seems to be statisfactory:

$$a=1.3x10^{13} \text{ dose/cm}^2 \quad (3)$$

is determined from the model. Since two carbon atoms are needed to produce N_{H_4slow} the data in Table II. suggest that about 20 % of all carbon atoms present participate in creating $C_S-Si_I-C_S$ at the saturation dose. Unfortunately the carbon concentration was measurable only in the C_{highC} samples, but our results do not contradict the IR absorption data for the other samples. (From the model $N_C=1x10^{16}$ cm^{-3} in the FZ samples and $N_C=8x10^{15}$ cm^{-3} for the CZ_{lowC} samples.)

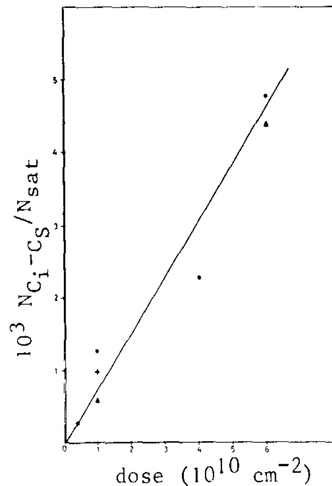

Figure 4
Experimental verification of equation 2.: FZ•, CZ_{lowC}+, CZ_{highC} ▲

CONCLUSIONS

It was shown that the dominant carbon related radiation damage level in silicon consists of two clearly separable components indentified as COV_2 and C_S-Si_I-C_S complexes.
The latter becomes the dominant defect at high doses and reaches a saturation value which is related to the overall carbon concentration in the sample.
The experimental data support this model which on the other hand offers a simple procedure to determine the overall carbon concentration by measuring N_{H_4slow} at any given proton dose. To calibrate accurately the proposed carbon concentration measurement procedure large number of samples with different and known carbon and oxygen concentrations are needed. It would also be important to correlate the value of parameter $\underline{a}$ in equation 2 with the influence of annealing.
The proposed carbon concentration measurement procedure of this paper should be viewed as a next step on the way to use H_4 for determining oxygen and carbon concentration in silicon as originally suggested by Troxell [9] . On the other hand it is clearly established that the slow component of H_4 is the C_S-Si_I-C_S complex wich forms via the interaction of mobile carbon interstitials with substitutional carbon. It is suggested that the measurement of the lateral distribution of the C_S-Si_I-C_S complexes by Scanning DLTS would reveal the oxygen precipitations around carbon atoms as nucleation sites.

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REFERENCES

* Permanent adress: University of Athens, Physics Department, Solid State Section, 104 Solonos Street, Athens, Greece.

[1] M.Kanamori and H.Tsuya, Jap.J.App.Phys. 1985, 24, 557
[2] F.Shimura, J.Appl.Phys. 1986, 59, 3251
[3] K.Irmscher, Thesis, Humboldt Universität, Berlin, GDR, 1985, unpublished
[4] L.C.Kimerling, P.Blood and W.M.Gibson, Inst.Phys.Conf.Ser. 1979, 46, 273
[5] L.C.Kimerling, Inst.Phys.Conf.Ser. 1977, 31, 221
[6] P.M.Mooney, L.J.Cheng, M.Süli, J.D.Gerson and J.W.Corbett, Phys.Rev. 1977, B15, 3836
[7] Y.H.Lee, L.J.Cheng, J.D.Gerson, P.M.Mooney and J.W.Corbett, Solid-State Com. 1977, 21, 109
[8] J.W.Walker and C.T.Sah, Phys.Rev. 1973, B7, 4587
[9] J.R.Troxell, Solid State Electron. 1983, 26, 539
[10] E.Sonder and L.C.Templeton, J.Appl.Phys. 1965, 36, 1811
[11] J.Bollmann, H.Klose and A.Mertens, Proc.Physik der Halbleiteroberfläche. 1984, 15, 247
[12] G.Ferenczi, C.A.Londos, T.Pavelka, M.Somogyi and A.Mertens, to be published
[13] G.Ferenczi, J.Boda and T.Pavelka, phys.stat.sol.(a), 1986, 94, K119
[14] G.Ferenczi, P.Krispin and M.Somogyi, J.Appl.Phys. 1983, 54, 3902
[15] Y.H.Lee, J.W.Corbett and K.L.Brower, phys.stat.sol.(a), 1977, 41, 637
[16] K.L.Brower, Phys.Rev. 1974, B9, 2607