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# PROPERTIES OF MULTILAYER MATERIALS IRRADIATED BY HIGH NEUTRON FLUENCES

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Multilayer materials based on silicon were exposed to fast neutrons with fluences ranging from $10^{15}$ to $10^{19}$ n/cm$^2$. $C-V$, deep level transient spectroscopy (DLTS) and $I-V$ measurements were carried out to analyse the properties of the respective layers as well as the $SiO_2$-(n-type)silicon and metal–(n-type)silicon interfaces. The detected divacancies and E-centres are likely the main cause of carrier reduction that has been found to depend on the initial doping concentration of the layer. This study has proven that both investigated interfaces exhibit radiation induced interface traps.

## 1. Introduction

The extent of the high energy neutron damage in silicon materials is often studied through evaluation of electrical properties [1,2]. Of main interest are the majority carrier concentration and recombination/generation carrier lifetime. Neutron radiation induced deep levels reported in Refs. 3 and 4 are assumed to be responsible for the rapid concentration changes, but the exact explanation of the carrier removal mechanism is still not clear. In this paper, the effect of fast neutrons on various multilayer structures exposed to a wide range of neutron fluences and temperature is reported, focusing on the majority carrier concentration.

## 2. *Experiment*

Different multilayer structures, $p^+$-n-$n_{ep}$-$n^+$ (structure A), $CrSi_2$-n(Si)-$n^+$ (structure B), and Al-$SiO_2$-n (structure C) structures were irradiated with fast neutrons of fluences ranging from $10^{15}$ to $10^{19}$ n/cm$^2$. Structure B exposed to $10^{16}$ n/cm$^2$ was annealed at 450 °C for 3 hours. The average energy of fast neutrons was 2 MeV and the temperature during irradiation reached 350 K.

A 6-7$\mu$m-thick epitaxial layer ($n_{ep}$) of structure A, with the concentration $N_d$ = (5-7)$\times 10^{15}$ cm$^{-3}$, was made on the substrate with resistivity $\rho < 0.008$ Ωcm. An n-layer of thickness of 1.7-2.2 $\mu$m was made by diffusion of phosphorus. In order to create the $p^+$-n junction, boron diffusion followed.

The same substrate was used for B-structures. An n-epitaxial layer with the concentration of $10^{16}$ cm$^{-3}$ was grown to the thickness of 4–8 $\mu$m. Then a Cr-layer was deposited by high-frequency cathode sputtering.

C–structures were formed by thermal oxidation of an antimony doped homogeneous wafer with orientation (100), resistivity of 2-5 Ωcm and thickness of 300 $\mu$m.

## 3. *Experimental results*

$C-V$, $I-V$ and deep level transient spectroscopy (DLTS) measurements were performed to determine electro-physical properties of the considered structures. Concentration profiles of the structures A and B were calculated from $C-V$ measurements. In order to evaluate saturation currents, $I_{sd}$ and $I_{sn}$, due to recombination in the depletion and neutral regions of the structure A on the basis of forward $I-V$ measurements, the model described in Ref. 5 (p. 141-142) was used. The forward current of the structure B was described formally by the same model with the substitute of $I_{sn}$ for thermionic saturation current $I_{te}$. The effective Schottky barrier height was calculated from $I_{te}$ using expression in Ref. 5 (p. 275).

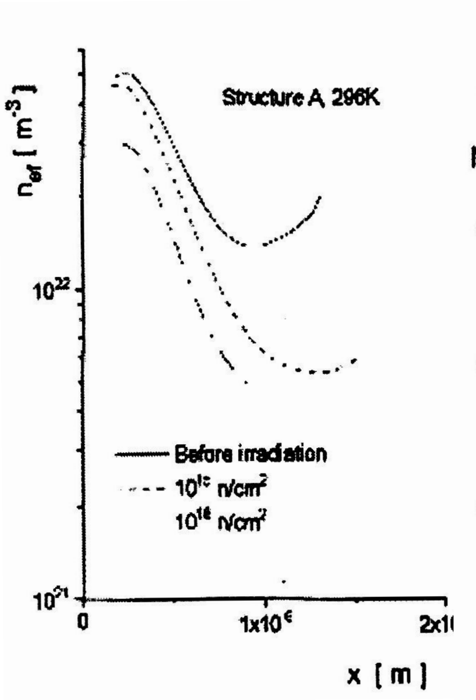
Assuming that the generation current is dominant for the reverse bias ($I_{sd} \gg I_{sn}$), what is easily fulfilled (as shown in Ref. 6) due to the presence of radiation defects, the generation lifetime $\tau_g$ can be calculated by using $C-V$ and reverse $I-V$ characteristics as follows

$$\tau_g = \frac{1}{2} A^2 q n_i \varepsilon_s \frac{\mathrm{d}(1/C)/\mathrm{d}V}{\mathrm{d}I/\mathrm{d}V} \tag{1}$$

where $A$ is the area, $q$ is the elementary charge, $n_i$ is the intrinsic concentration and $\varepsilon_s$ is the silicon permittivity.

## *4. Discussion*

It is evident from carrier concentration profiles (Figs.1 and 2) that the effective carrier concentration in structures A and B is reduced as the neutron fluence increases. High frequency $C - V$ measurements of the structure C showed, after irradiation, a drop of capacitance from about 230 pF to less than 2 pF that also implies the carrier removal. There is also a significant change of carrier concentration with temperature for irradiated structures B compared to those before irradiation or after annealing (Fig. 2).



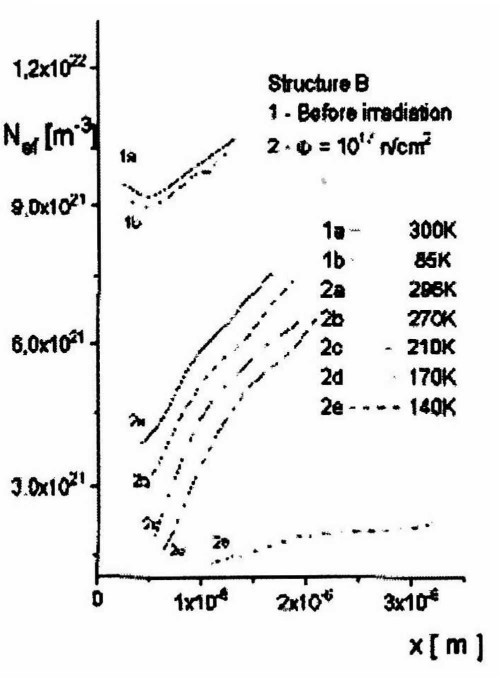



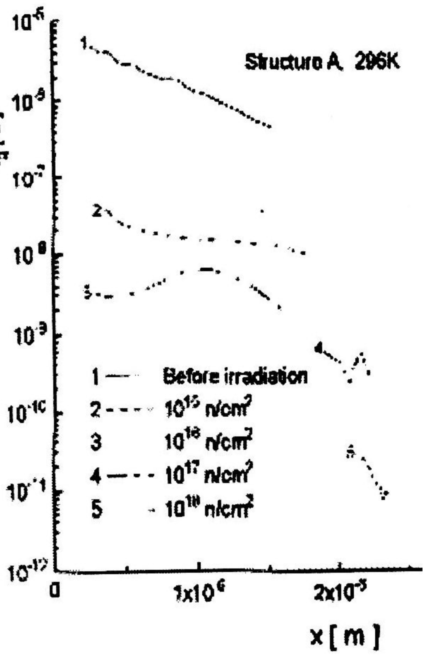

*Fig. 1. Effective carrier concentration profile of the n-layer of the structure A for various neutron fluences. The point $x = 0$ corresponds to the interface $p^+$-n.*

*Fig. 2. Effective carrier concentration profile of the n-layer of the structure B before irradiation (1) and that exposed to $10^{17}$ n/cm$^2$ (2) at various temperatures. The point $x = 0$ corresponds to the interface* Cr-Si *(right).*

The carrier concentration profiles of the structure A for various fluences indicate that the relative change of concentration after irradiation depends on the initial value of the doping concentration. If we assume a linear dependence of the defect concentration on the neutron fluence, then the critical neutron fluence $\phi_{crit}$, for a 25% change of majority carrier concentration at room temperature, can be described by

$$\phi_{crit} = c(E, T_i) N_d \tag{2}$$

where $c(E, T_i)$ is the coefficient depending on the average energy of neutrons, $E$, and the temperature, $T_i$, during irradiation, and $N_d$ is the doping density. In our experiment, $c = 0.2$ cm has been found. The critical doping densities of structure A, B and C were $5{\times}10^{16}$, $10^{16}$, and $10^{15}$ cm$^{-3}$, respectively. According to Eq.(2), the corresponding critical fluences were $1{\times}10^{16}$, $2.0{\times}10^{15}$ and $2.0{\times}10^{14}$ n/cm$^2$, respectively, which is consistent with our observations. Although the assumption of the linearity of the defect creation with an increasing fluence seemed strong, Eq.(2) matches the research reported in Refs. 4,7 and 8. In addition, studies on the lattice damage [9] proved that defects are not spatially overlapped even at the neutron fluence of $10^{19}$ n/cm$^2$.



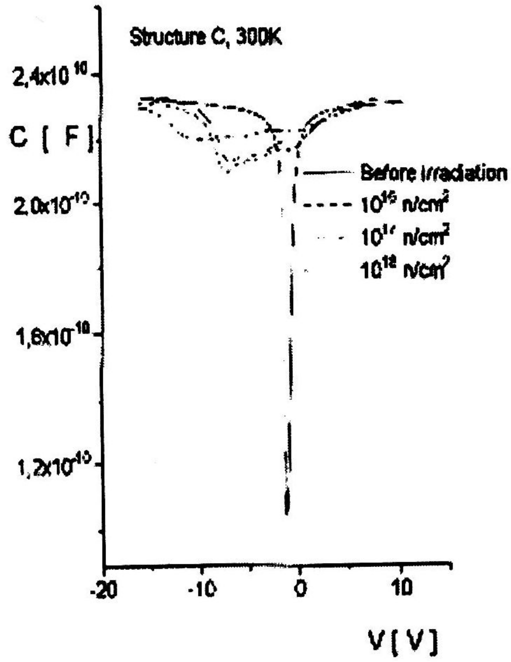




*Fig. 3. Generation time as a function of the depth in the n-layer of the structure A for various neutron fluences.*

*Fig. 4. Quasistatic characteristics of the structure* C *for various neutron fluences (right).*

All these rapid concentration changes are induced by the existence of deep levels in the band gap, which act as generation/recombination centres [4,10,11]. Our DLTS measurements of the structure B have detected a broad level complex associated around the dominant level $E_c$-0.41 eV (divacancy and/or E-centre) and the centre at $E_c$-0.27 eV in the case of the structure B exposed to $10^{17}$ n/cm$^2$. Similarly, a distinct deep level complex with the major centre at $E_c$-0.39 eV was found after exposing the sample B to $3\times10^{17}$ n/cm$^2$. On the basis of comparison of the DLTS signal between annealed structure B and that exposed to $10^{17}$ n/cm$^2$, four centres at $E_c$-0.27 eV, $E_c$-0.38 eV, $E_c$-0.49 eV and $E_c$-0.52 eV in the annealed structure have been found responsible for a creation of the level complex mentioned above. Annealing strongly suppressed the level complex at around $E_c$-0.41 eV and this implies that the main cause of the carrier removal can be attributed to this complex.

Defects speed up generation which results in the decrease of generation lifetime, particularly those with levels located around the band gap. The large concentration of radiation–induced defects is evident from the strong dependence of the generation carrier lifetime on the neutron fluence for the structure A (Fig.3), which fell from about $2\times10^{-6}$ s before irradiation to $10^{-11}$ s when exposed to $10^{18}$ n/cm$^2$. On the other hand, the saturation current $I_{sd}$ of the structure A increased from $9.0\times10^{-13}$ A before irradiation to $1.5\times10^{-7}$ A after being exposed to $10^{19}$ n/cm$^2$.

As it follows from quasistatic $C-V$ measurements of the structure C (Fig. 4), there is such a number of interface traps at $SiO_2$-Si that beginning of strong inversion is shifted by 10-15 V after irradiation. Fast neutrons, basically, seem to effect any interface since the Schottky barrier height, which is also dependent on the state of the interface Cr-Si, changes within 0.612-0.655 eV for different neutron fluences.

## 5. *Conclusion*

It has been found that the reduction of the carrier concentration depends not only on the neutron fluence but also on the initial doping concentration. That must be taken into consideration when a multilayer structure is subjected to neutron irradiation. The decrease of the carrier concentration is attributed to the level complex at the dominant energy $E_c$-0.41 eV. This is supported by a strong susceptibility of the carrier concentration of the irradiated structures (structure B) to temperature and by the changes in the generation carrier lifetime and of the leakage current ($I_{sd}$, structure A) within several orders of magnitude.

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## SVOJSTVA VIŠESLOJNIH MATERIJALA OZRAČENIH JAKIM NEUTRONSKIM TOKOVIMA

Višeslojni materijali na osnovi silicija izloženi su brzim neutronima tokovima od $10^{15}$ do $10^{19}$ n/cm$^2$. Mjerenja $C-V$, prijelazna spektroskopija dubokih stanja i $I-V$ mjerenja načinjeni su radi analize svojstava višeslojeva kao i $SiO_2$ – (n-silicij) te metal – (n-silicij) granice. Čini se da su glavni razlog smanjenja nositelja opažene dvojne šupljine i E-centri, koji ovise o početnoj koncentraciji dodataka (dopanata) u sloju. Pokazano je da obje istraživane granice sadrže klopke uzrokovane ozračivanjem.