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GENERATION OF SURFACE STATES ON THE Si–SiO$_2$ INTERFACE UNDER THE INFLUENCE OF SYNCHROTRON RADIATION

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A dose dependence analysis of the origin of surface states under the influence of synchrotron radiation has been performed. Quantity estimates of the exposure dose absorbed by the investigated samples, and also analysis of the surface states' relaxation process under thermal treatment have been done. It has been shown that short-time, low-temperature annealing restores the parameters of the samples to the initial level.

With its outstanding features such as a continuous spectrum, high spectral brightness over the entire spectrum, high natural collimation degree and temporal stability of its characteristics, synchrotron radiation (SR) has become a powerful tool in submicron technology and analytical studies [1].

However, due to the fact that the SR beam has such a high spectral brightness value (2–4 orders of magnitude more than that of the most powerful conventional X-ray tube with a rotating anode [2]) the danger exists of the appearance of radiation damage in samples to be investigated using SR beams. It can unpredictably destroy silicon wafers during their production. In our early work (see ref. [3]), when topographic exposures of gadolinium gallium garnet crystals were made, we observed the appearance of some color centers after the experiment. In ref. [4], investigating the influence of the SR beam on the electric parameters of the Si–SiO$_2$ interface, we have shown that the surface state density on the Si–SiO$_2$ interface increases with increasing exposure time. However, such a dependence is not universal and belongs to the particular SR source used in the experiment. Our aim was to analyse the dependence of the surface state density on the exposure dose absorbed in the Si–SiO$_2$ interface of metal-oxide-silicon (MOS) structures.

So we have calculated the exposure dose absorbed by a sample. Following ref. [5], first of all, we have found the spectral illuminance $A(\lambda)$ of the source at a distance L with the help of the formula

$$A(\lambda)\left[\frac{\mathrm{W}}{\mathrm{mm^2 Å}}\right] = \frac{59E^2[\mathrm{GeV}]I[\mathrm{A}]}{\lambda[\mathrm{Å}]L^2[\mathrm{m}]}\eta\left(\frac{\lambda}{\lambda_c}\right)\nu^{-1}\left(\frac{\lambda}{\lambda_c}\right)\frac{\Delta\lambda}{\lambda}, \qquad (1)$$

where E is the electron beam energy, I is the electron beam current, λ_c is the critical wavelength, $\eta(\lambda/\lambda_c)$ and $\nu(\lambda/\lambda_c)$ are the average spectral and angular distribution functions, respectively, for radiation from the bending magnet of the SR source. Then we have obtained the spectral illuminance absorbed by a specimen using the values of the total mass absorption coefficients for beryllium, $\mu_{Be}(\lambda)$, and air, $\mu_A(\lambda)$, and also the real absorption coefficients of silicon, $\mu_{Si}(\lambda)$:

$$C(\lambda) = A(\lambda)\,\mathrm{e}^{-(\mu_{Be}t_{Be}+\mu_A t_A)}\left(1-\mathrm{e}^{-\mu_{Si}t_{Si}}\right), \qquad (2)$$

where t_{Be}, t_A, t_{Si} are the thicknesses of the beryllium foils, the air gap between the exit beryllium foil and the sample, and the silicon specimen, respectively. Integrating eq. (2) over all wavelengths, we obtained the exposure dose, D, absorbed by the sample:

$$D[\mathrm{Rad}] = C_\Sigma\left[\frac{\mathrm{W}}{\mathrm{kg}}\right]T[\mathrm{s}], \qquad (3)$$

where C_Σ is the integrated illuminance absorbed by the sample and T is the exposure time.

Experiments were conducted using the VEPP-4 storage ring. Its parameters were: $E = 5.5$ GeV, $\lambda_c = 0.83$ Å, $I = 0.01$ A, $L = 23.5$ m. Five beryllium foils (total thickness 1 mm) were installed on the beam line of the facility. The air gap thickness was 10 cm. The samples were prepared as described in ref. [6]. The methods of measuring the surface state density are described in ref. [4]. The total thickness of the MOS structures was 380 μm.

The dependences of the illuminance of the SR source and of that absorbed by the samples, calculated by means of eqs. (1) and (2), are depicted in fig. 1a (curves 1 and 2, respectively).

The increment of the surface state density dependence, ΔN_{ss}, on the exposure dose, calculated by using eq. (3), is depicted in fig. 1b (curve 1). It appears that the surface state density generated on the Si–SiO$_2$ inter-

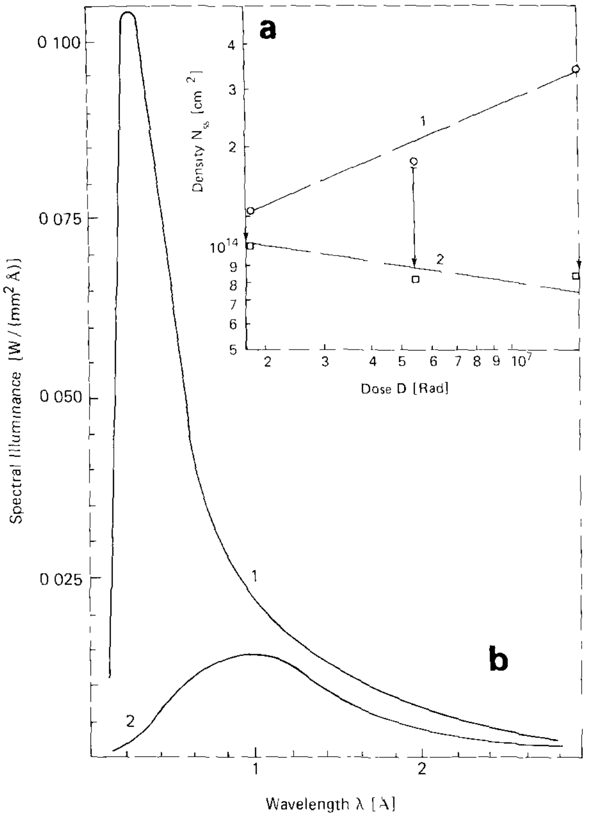

Fig. 1. (a) The spectral dependence of the illuminance of the SR source (1) and that absorbed by the sample (2). (b) Dose dependence of the increment of the surface state density ΔN_{ss} measured after exposure (1) and after keeping at room temperature for two months.

face by the SR beam increases as the exposure dose increases and can be approximated by the power function:

$$N_{ss1} = N_{ss0}(1 + QD^{B}), \tag{4}$$

where the constants are: $N_{ss0} = 1 \times 10^{12}$ cm^{-2}, $Q = 5.6 \times 10^{-2}$, $B = 0.46$. The surface state density decreased gradually after the samples had been kept at room temperature for two months. It appears that the relaxation degree increases with increasing exposure dose and, hence, with increasing damage density, ΔN_{ss}, caused by the exposure (curve 2 in fig. 1b). Curve 2 in fig. 1b can also be approximated by the power function

$$N_{ss2} = N_{ss0}(1 + RD^{K}), \tag{5}$$

where the constants are: $N_{ss0} = 1 \times 10^{12}$ cm^{-2}, $R = 1.15 \times 10^{3}$, $K = -0.15$. The process of restoration can be approximated by the expression obtained by subtracting eq. (5) from eq. (4):

$$\Delta N_{ss} = G(SD^{\kappa} - 1)D^{\xi}, \tag{6}$$

where the constants are: $G = 1.2 \times 10^{15}$, $S = 4.6 \times 10^{-5}$, $\kappa = 0.60$, $\xi = 0.15$.

It should be noted that complete relaxation of N_{ss} was observed only in the case of increasing the annealing temperature up to 150 °C. Annealing during 30 min resulted in returning N_{ss} to its initial level.

Thus it has been shown that using synchrotron radiation results in the generation of surface states on the Si–SiO$_2$ interface. However, short-time, low-temperature annealing restores the parameters of the investigated structures to the initial level. It has also been shown that using synchrotron radiation in submicron technology and analytical studies has a nondestructive character.

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