

# Comparison of interface-state generation by 25-keV electron beam irradiation in *p*-type and *n*-type MOS capacitors

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The interface state induced by 25-keV electron beam irradiation in MOS capacitors having *p*- and *n*-type substrates with several different doping concentrations have been studied. For radiation dosage on or above the order of  $1 \times 10^{-5}$  C/cm<sup>2</sup>, all of the radiation-induced interface-state distributions tend to have a similar shape which is asymmetrical about the midgap, independent of the type and concentration of the silicon dopants, and independent of the initial interface-state distributions. The states in the upper half of the silicon band gap are acceptor type which peak around 0.2 eV from the midgap, whereas the states in the lower half of the band gap are donor type with a lower density. For radiation dosage below  $1 \times 10^{-7}$  C/cm<sup>2</sup> the postirradiation interface states are proportional to their initial values. An explanation based on the broken bond model is presented to account for the observations.

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It is known that exposure to ionizing radiation can cause an increase in the density of electronic states located at the silicon-silicon-dioxide interface.<sup>1-4</sup> A buildup of such states causes a decrease in the transconductance of MOS transistors. It also contributes to a change in threshold voltages. In this letter we report the generation of interface states in MOS capacitors with *p*-type and *n*-type silicon substrates having several different doping concentrations.

Three boron-doped *p*-type wafers (doping concentration  $1 \times 10^{14}$ ,  $9 \times 10^{14}$ , and  $5 \times 10^{15}$ /cm<sup>3</sup>, respectively) and two arsenic-doped *n*-type wafers (doping concentration  $4 \times 10^{14}$  and  $3 \times 10^{15}$ /cm<sup>3</sup>) were used in this experiment. All wafers had a (100) surface orientation. Approximately 500-Å thermal oxides were grown in dry O<sub>2</sub> at 970 °C for 80 min, followed by a 30-min *in situ* N<sub>2</sub> anneal. Then, approximately 5000 Å of pure Al was evaporated from a heated Ta boat through a metal mask producing a 10×10 array of 20-mil-diam dots. After annealing the dots at 400 °C for 1 h in a mixture of hydrogen and nitrogen gas, high-frequency and quasistatic *C-V* data were taken to determine the preexposure interface-state density<sup>5</sup> which was found to be in the mid  $10^{10}$ /cm<sup>2</sup> range. After the measurements, the wafers were irradiated by a 25-keV electron beam. During the irradiation the metal gates were left floating. Each wafer received four different doses:  $1 \times 10^{-5}$ ,  $1.6 \times 10^{-5}$ ,  $6.6 \times 10^{-5}$  C/cm<sup>2</sup>, and "stray" irradiation, on different quadrants of the wafer.<sup>6</sup> After the exposure, the high-frequency and quasistatic *C-V* measurements were made again to determine the postexposure interface-state distribution.

Figure 1 shows the postexposure interface-state distribution as a function of energy in the silicon band gap for five different samples. The radiation dose used in this case was  $1.6 \times 10^{-5}$  C/cm<sup>2</sup>. However, the following discussion holds for the other two doses used in the experiment as well. The salient feature of Fig. 1 is that all five samples show a peak in the upper half of the band gap centered around 0.2 eV from the midgap despite their different dopant types and concentrations. The small differences in the peak energy locations may

be due to experimental errors. There does not seem to be a simple relationship between the magnitude of the peaks and the type or concentration of the substrate

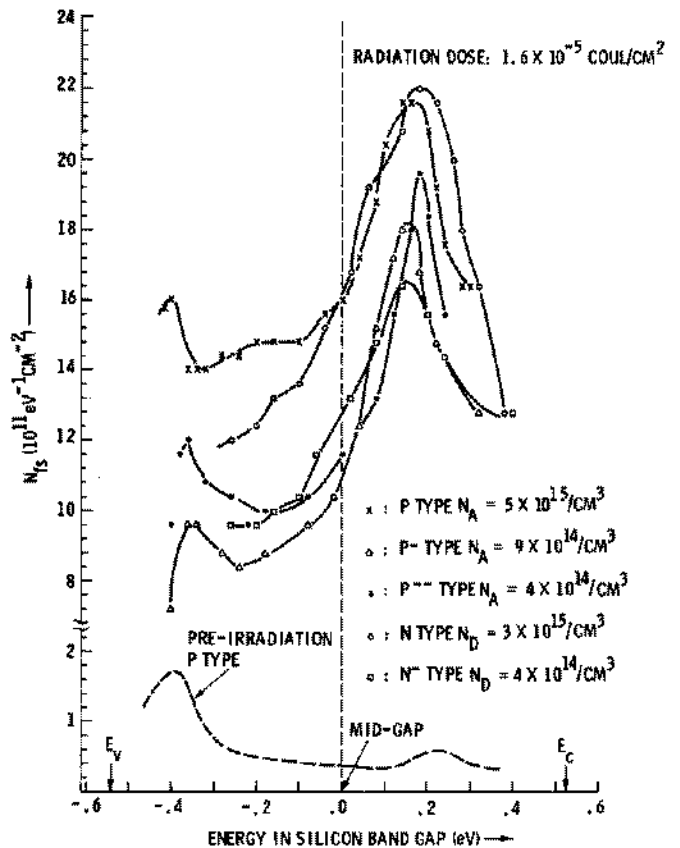


FIG. 1. Interface-state distribution after electron-beam irradiation (dosage  $\sim 1.6 \times 10^{-5}$  C/cm<sup>2</sup>) as a function of energy in the silicon band gap for three *p*-type and two *n*-type MOS samples having different doping concentrations. The states in the upper half of the band gap are believed to be acceptor type and those in the lower half of the band gap to be donor type. The preirradiation distribution for a *p*-type MOS is also shown for comparison.

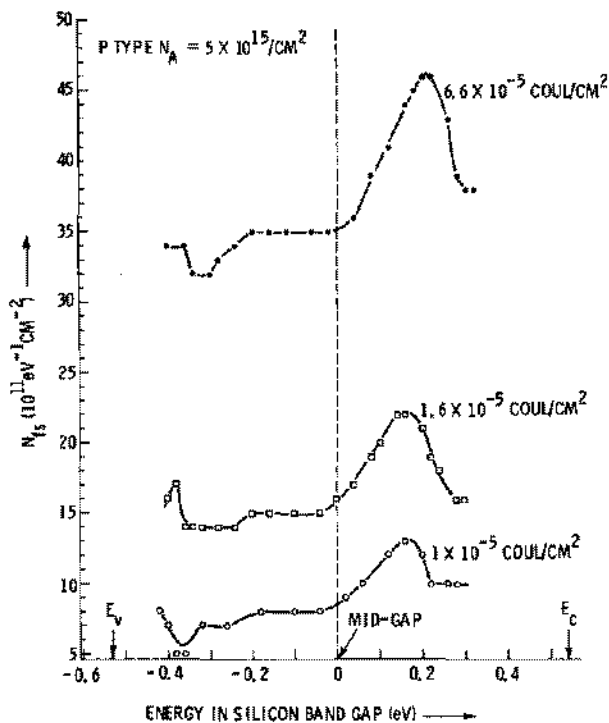


FIG. 2. Radiation-induced interface-state distribution for a  $p$ -type MOS for three different doses.

dopants. In fact, as will be shown, the magnitude depends strongly on the exposure dosage so that variations of the beam current during exposure could easily wash out any subtle difference, if any, arising from the different dopants.

Figure 2 shows the dosage dependence of the post-radiation interface-state distribution for a  $p$ -type sample which is typical of all the samples tested.

It should be noted that the shape of the initial surface-state distributions before the irradiation (dotted curve in Fig. 1, for example) in general are quite different from the postradiation ones. This seems to disagree with the observations of Sivo *et al.*,<sup>4</sup> who reported that the radiation-induced increases in the interface-state density are proportional to the preirradiation density at each energy location. A close examination of their paper, however, revealed that the radiation dosage used in their experiments (Figs. 3, 4, and 5 in Ref. 4) was always below  $5 \times 10^6$  rad which is 2 orders of magnitude lower than the dosage in our experiment ( $\approx 5 \times 10^7$  rad). To confirm that the apparent discrepancy is a result of the much higher dosage, we then plotted out the interface-state distribution for a few dots that only received "stray" irradiation.<sup>6</sup> Figure 3 shows a typical result of such a dot. The dosage in this case is estimated to be below  $1 \times 10^5$  rad which is well in the range of Sivo *et al.*'s experiment.<sup>4</sup> Note that apart from the over-all increase of a factor of 3, the postradiation curve is almost a replica of the initial curve. A systematic experiment is being conducted to investigate the limit of the dosage range above which the surface-state distribution begins to show the high-dosage effect.

From the shape of the high-frequency  $C$ - $V$  curves, the surface states in the upper half of the band gap were determined to be acceptor type, while those in the lower half of the band gap were determined to be donor type, for all the  $n$  and  $p$  samples examined. The charged acceptor states could cause a positive shift in the flat-band voltage, while the charged donor states could cause a negative shift. Since the densities of the post-radiation interface states are very high, one must be very careful in the interpretation of radiation effect results based solely on the flat-band shift data. For example, only negatively charged acceptor states between the Fermi level and the midgap would contribute to the flat-band shift (positive shift) in an  $n$ -type sample, while only positively charged donor states would contribute (negative shift) in a  $p$ -type sample. Furthermore, the asymmetry of the interface-state distribution would tend to affect the  $n$ -type sample more than the  $p$ -type sample. These points will be elaborated on in a subsequent paper.

At present, the origin of the radiation-induced interface states is not clear. The results of the present investigation, however, appear to be consistent with the broken bond model<sup>7</sup> or the structural modification model<sup>8</sup> which suggests that the interface states resulting from exposure to radiation are caused by structural modifications of the  $\text{SiO}_2$  layer. This change in structure of the  $\text{SiO}_2$  film causes many of the bonds at the  $\text{SiO}_2$ - $\text{Si}$  interface to be broken, which in turn produces interface states. It was also suggested that electrons with such a low energy could only break bonds that were initially strained.<sup>7</sup> In accordance with this model, the following is proposed to explain our present results: Initially, due to the nature of the thermal growth process, there may exist many more strained bonds (per unit volume) near the  $\text{SiO}_2$ - $\text{Si}$  interface than in the bulk  $\text{SiO}_2$  film. These strained bonds near the interface are likely to gather around the interface-state centers which themselves are "dangling" bonds. Therefore, statistically speaking, these strained bonds near the interface

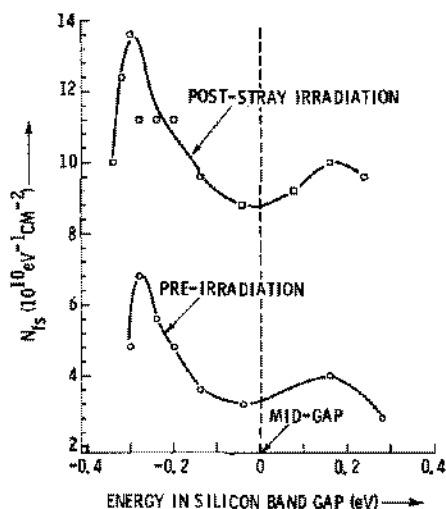


FIG. 3. Interface-state distribution in the silicon band gap before and after low-dosage electron beam irradiation (dosage  $< 1 \times 10^7$  C/cm<sup>2</sup>).

are affected sooner than those in the bulk  $\text{SiO}_2$  film; that is, these strained bonds are broken even before any major structural modification of the  $\text{SiO}_2$  film takes place. Since these newly broken bonds are assumed to be located near the initial "dangling" bonds, they are likely to have similar energy levels to the initial interface states owing to their similar surrounding physical environment. As a consequence, one observes a proportional increase in the radiation-induced interface-state distribution as shown in Fig. 3. As the radiation dosage is increased beyond a certain level, however, a large number of the strained bonds in the  $\text{SiO}_2$  bulk are broken, resulting in a shrinkage of the film<sup>7-9</sup> which in turn causes many more initially "normal" bonds at the interface to be broken. Consequently, many more interface states are generated which do not track the initial distribution as evidenced in Fig. 1. Since, to first order, the latter mechanism is essentially independent of the type and the doping concentration of the silicon substrate, one should not expect the radiation-induced interface states to depend on the dopant type and concentration of the silicon, which is consistent with our observations.

Another possibility cannot be completely ruled out; that is, that the original  $\text{SiO}_2$  might be hydrated as a result of the postmetalization anneal. During the electron bombardment, a hydrogen-related center at the  $\text{SiO}_2$ -Si interface might capture an electron which broke the bond between the hydrogen and the center permitting the hydrogen to escape, as described by Nicollian *et al.*<sup>10</sup> Consequently, many interface states were formed in this fashion. While such a mechanism is not unlikely, many of our results cannot be satisfactorily explained by this model (which will be referred to as the "hydrogen model"). For example, it is not clear, based on the hydrogen model, why the radiation-generated interface-state distribution for the low-dosage electron beam should track their initial shape (as in Fig. 3), while those for the high-dosage beam should consistently approach a different shape (as in Fig. 2). In addition, the hydrogen model calls for a large num-

ber of electrons trapped at the interface<sup>10</sup> (on the order of the number of interface states), which have never been observed. Furthermore, we have observed that the density of the electron-beam-induced interface states depends strongly on the oxide thickness. For a given electron dosage and for the same quality dry oxides, the density of the radiation-induced interface states increases significantly as the oxide thickness increases from 90 to 900 Å.<sup>11</sup> This result again cannot be simply related to the hydrogen model. On the other hand, most of the presented data are consistent with the broken bond model mentioned earlier, including the oxide-thickness results which will be discussed in more detail in a subsequent paper.

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