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Characterization of Electron Traps in Aluminum-Implanted SiO_2

Abstract: Johnson, Johnson, and Lampert have studied the effect of Al implantation on the trapping behavior of SiO_2. The large fluence that they used (1×10^{14}Al/cm^2) and the low annealing temperatures (up to 600°C) resulted in a trapping efficiency of 1 and made it impossible to characterize the traps. In the present study a lower fluence and higher annealing temperatures to reduce the trapping efficiency are used to permit characterization of the traps. The predominant trap cross sections are 1.26×10^{-16} and 1.40×10^{-17} cm^2. In a companion paper by DiMaria, Young, Hunter, and Serrano the location of the trapped charge is discussed.

Introduction

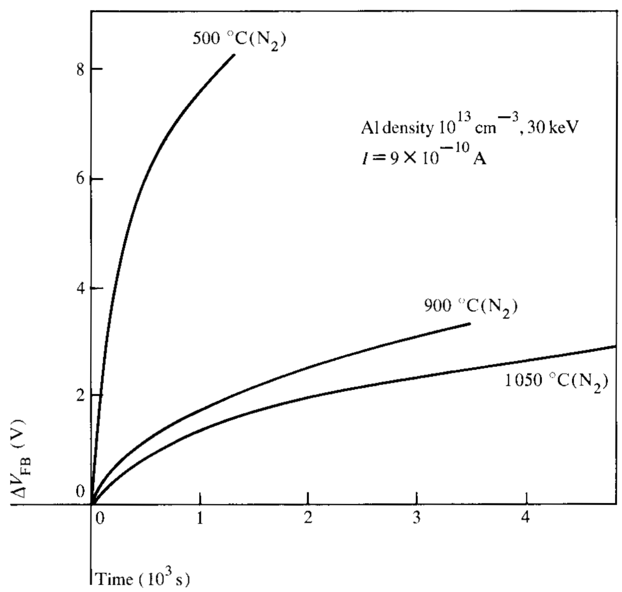
The effect of Al implantation on the electron trapping behavior of SiO_2 has been studied by Johnson, Johnson, and Lampert [1] in MOS structures. They used a fluence of 1×10^{14} Al ions/cm^2 at 20 keV and a SiO_2 thickness of 140 nm. Their work indicated that most of the traps were due to displacement damage. The maximum annealing temperature was 600°C. Most of the work, however, was done with unannealed samples. In a recent paper by D. R. Young, D. J. DiMaria, and W. R. Hunter [2] some data were presented showing that annealing temperatures up to 1050°C result in a substantial reduction in the trapping rate. These data are given in Fig. 1. It was hoped that the high temperature anneals would eliminate the displacement damage and enable us to study the trapping associated with the Al sites. We have also varied the SiO_2 thickness between 49 and 140 nm and the implantation energy from 15 to 40 keV. The location of the trapped charge has been studied on the samples by DiMaria, Young, Hunter, and Serrano [3], who used the photo *I-V* technique.

Experiments

• *Sample preparation*

Silicon p-type wafers are used with a resistivity of 0.1 to 0.2 ohm-cm. The SiO_2 is grown at 1000°C in a dry oxygen environment. The samples are ion implanted, cleaned, and annealed at 1050°C for 30 min. As soon as possible after the heat treatment, Al is applied by evaporation in the form of dots 0.080 cm in diameter, followed by post-metallization annealing at 400°C for 30 min in N_2.

Figure 1 Flat-band voltage shift as a function of time for various annealing temperatures. The annealing time is 30 min.



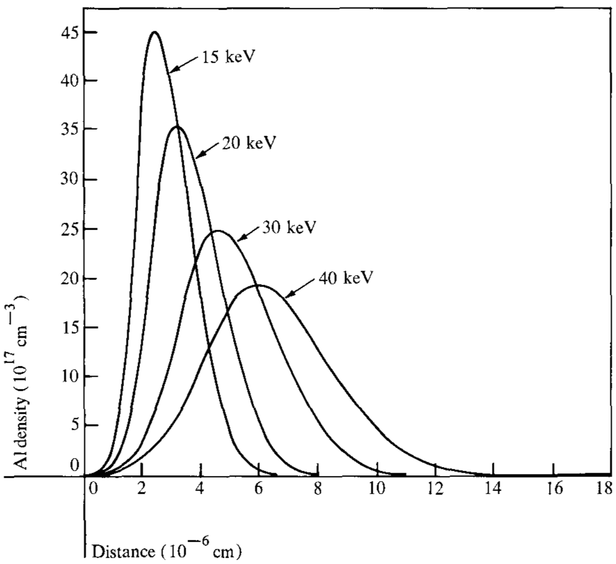


Figure 2 Aluminum concentration profiles calculated by using LSS theory for various implantation energies. The fluence is 1×10^{13} Al/cm^2.

- *Measurement technique*

An electron current is induced in the SiO_2 by using avalanche injection from the Si [4, 5]. A feedback circuit is inserted between the output of the electrometer used to measure the current and a 500-kHz square wave generator. This circuit controls the amplitude of the square waves and maintains the current in the SiO_2 at a value that can be preset as desired. As trapping occurs, the square wave amplitude is automatically increased to compensate for the effect of the trapped charge. The square waves are interrupted periodically to measure automatically the flat-band voltage as a means for monitoring the trapped charge buildup in the SiO_2. The circuits used are described in an earlier paper [2]. In the course of a typical run 400 to 600 measurements are made. These data are fed into a computer and the results are analyzed to provide information concerning the trap cross sections and the trap densities. The computer program can resolve two different traps if their cross sections are separated by at least a factor of two. The analysis of the results follows the same procedure followed by DiMaria, Aitkin, and Young [6]. The SiO_2 current used depends on the cross sections of interest and in this particular experiment the range was 9×10^{-10} to 9×10^{-9} A. The largest current is used for the small cross section traps. The change in flat-band voltage is given by

$$\Delta V_{FB} = Q\bar{x}/C_{ox} L, \quad (1)$$

where C_{ox} is the SiO_2 capacity per unit area, L is the SiO_2 thickness, Q is the trapped charge per unit area, and $\bar{x}$ is the distance of the centroid of the trapped charge from the Al-SiO_2 interface. Because the flat-band voltage measurement does not enable us to determine Q and $\bar{x}$ independently, we refer to an effective charge given by

$$Q_E = Q\bar{x}/L. \quad (2)$$

Ning and Yu [7] have shown that these considerations do not affect our measurements of the trap cross sections.

We obtain the cross sections and the effective trap densities by fitting exponentials to our data. The cross section is given by

$$\delta = q/\tau I, \quad (3)$$

where τ is the time constant of the exponential, I is the current density, and q is the charge on the electron. The magnitude of the exponentials gives us the effective density of the traps. The charge centroid correction must be used to obtain the actual density.

The implanted Al profiles have been calculated by using the Lindhard-Scharff-Schøtt (LSS) range statistics calculated by Gibbons, Johnson, and Mylroie [8]. Their data have been corrected for the lower density of our SiO_2 as compared with single-crystal quartz. The factor used is 0.84. These profile calculations are shown in Fig. 2. It can be seen that for our thinnest sample (D_{ox} = 49 nm), penetration of the Si by Al ions should be appreciable for an implantation energy of 20 keV. Results are presented indicating that substantial penetration actually occurs even for the 15-keV implantation.

If we substitute the expression for $C_{ox}(C_{ox} = \varepsilon/L)$ into Eq. (1), we obtain for the flat-band voltage shift

$$\Delta V_{FB} = Q\bar{x}/\varepsilon, \quad (4)$$

where ε is the dielectric constant of SiO_2. This relationship is independent of L, and thus we see that V_{FB} should not depend on L if Q and $\bar{x}$ are independent of L. We assume that this is the case if the implanted Al does not reach the Si-SiO_2 interface.

- *Experimental results*

An accurate characterization of the traps requires that ΔV_{FB} for the implanted sample be large compared to the unimplanted sample for the same charging conditions. The earlier work [2] has shown that this is the case if we use a fluence of 1×10^{13} Al/cm^2 and for implantation energies that result in the peak of the implanted profile being located near the center of the SiO_2. For larger implantation energies we lose Al to the Si and for smaller implantation energies ΔV_{FB} is smaller due to the charge centroid effect. Although we present data for comparison that do not satisfy this criterion, we use only the data taken near the optimum condition to characterize the traps.

The experimental results are given in Figs. 3 (a)–(c) for L = 140 nm, 73 nm, and 49 nm, respectively. In the case of Fig. 3(a) (140 nm), we see a large increase in the trap-

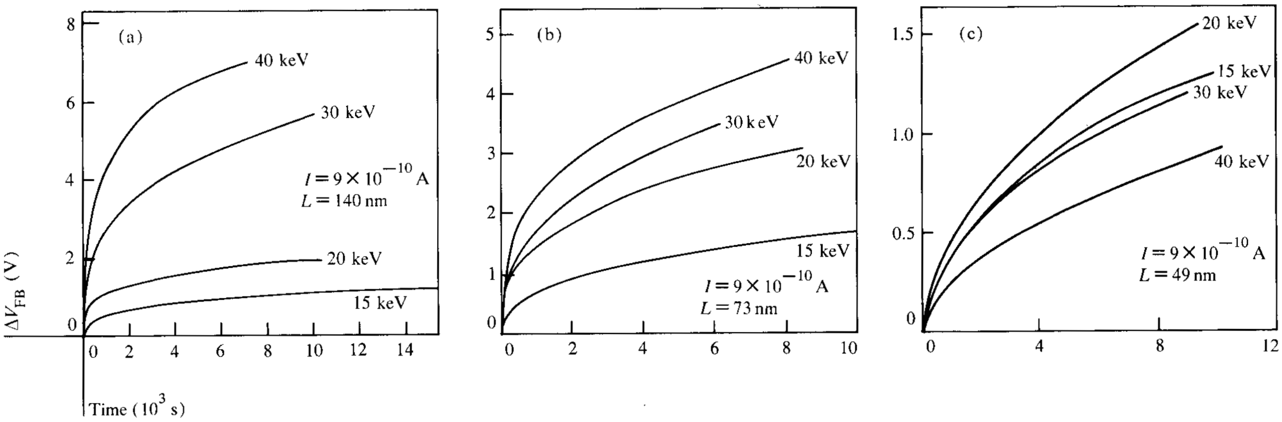


Figure 3 Flat-band voltage shift as a function of time for various implantation energies. (a) L = 140 nm; (b) L = 73 nm; (c) L = 49 nm.

ping (ΔV_{FB}) as the implantation energy increases; a significant but smaller increase is noted in Fig. 3(b) (73 nm), and in Fig. 3(c) (49 nm), it is seen that the trapping actually decreases for implantation energies above 20 keV. The fluence in all cases is 1×10^{13} Al/cm^2. The change in these results with L is due to the penetration of the Si by the Al ions. This is shown by Fig. 4, where ΔV_{FB} is a function of L, and not independent of L as predicted by Eq. (4). These results indicate that penetration certainly occurs for L = 73 nm and V_I = 30 keV.

The large increase in trapping with the implantation energy (V_I) shown by Fig. 3(a) (L = 140 nm) is a surprising result. The average shift $(\Delta V_{FB})_{avg}$ taken from these data is plotted as a function of implantation energy (V_I) on a log-log plot in Fig. 5 and we see that the slope is two, indicating that the trapping varies as V_I^2. The increase in the charge centroid distance $\bar{x}$ has been shown by DiMaria to be proportional to V_I. These results indicate a linear dependence of the trap density on the implantation energy.

A summary of the measured trap densities and cross sections is given in Table 1. The total effective trap concentration observed is 3.5×10^{12}. The charge centroid measurements of DiMaria et al. [3] indicate that $\bar{x}/L$ = 0.59 for this case. Using this correction results in an actual trap density of 5.93×10^{12} as compared with the implanted fluence of 1×10^{13} Al/cm^2. Since the trap density depends on V_I and is reduced if we have penetration of the Si, we must regard this trap density as applying only to this particular case.

Discussion of results

Our results for the thick SiO_2 (L = 140 nm), which does not allow penetration of the Si by the Al ions through the SiO_2, show that the trapping varies as the square of the implantation energy. The charge centroid position mea-

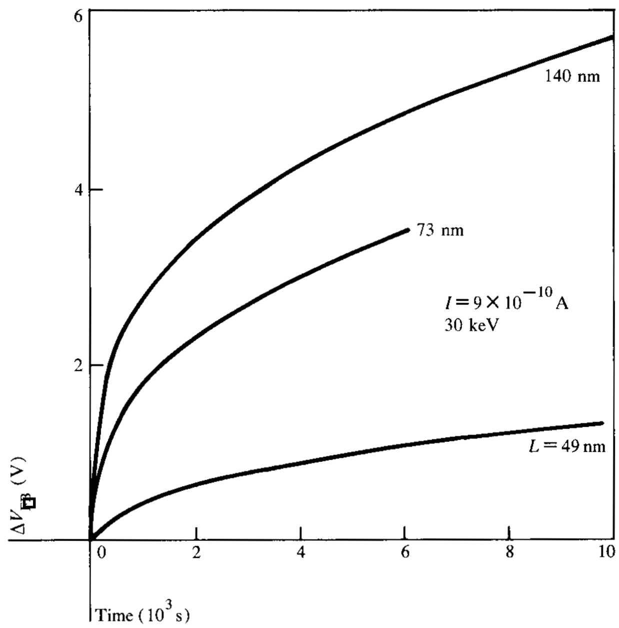


Figure 4 Flat-band voltage shift as a function of time for various SiO_2 thicknesses.

Table 1 Trap cross sections (σ) and effective densities (N_t) for the traps resulting from a 30-keV Al implant with a fluence of 1×10^{13} Al/cm^2 and L = 73 nm.

$\sigma(cm^2)$	$N_t(cm^{-2})$
1.60×10^{-15}	4.60×10^{11}
1.26×10^{-16}	1.14×10^{12}
1.40×10^{-17}	1.40×10^{12}
1.26×10^{-18}	5.00×10^{11}

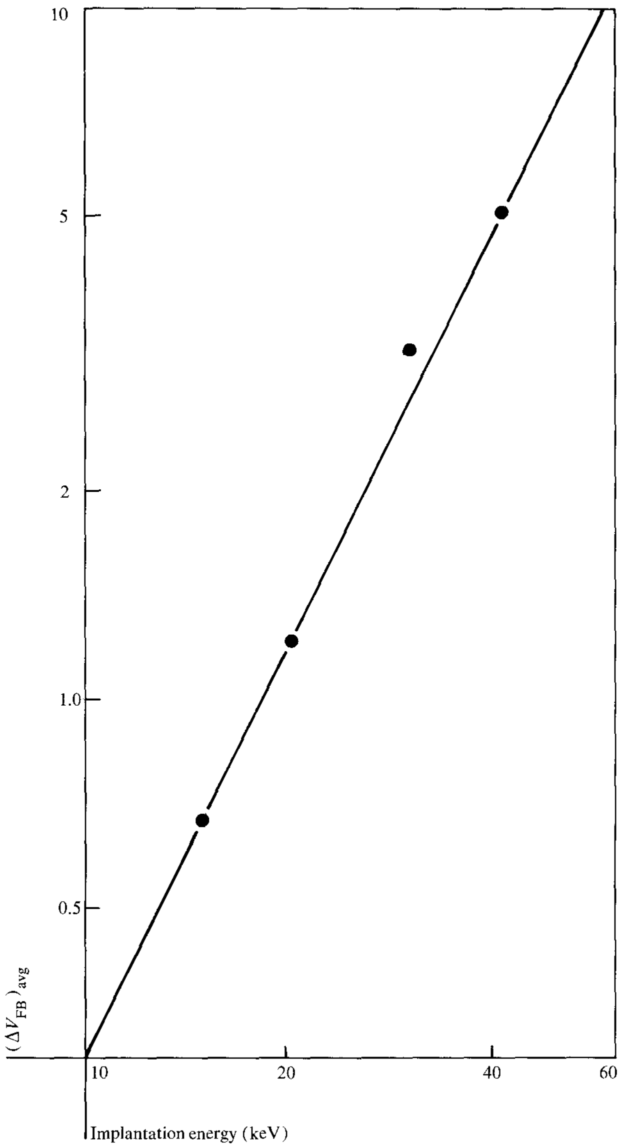


Figure 5 Log-log plot of $(\Delta V_{FB})_{avg}$ taken to 6500 s as a function of implantation energy. The average flat-band voltage shift $(\Delta V_{FB})_{avg}$ is the sum of the shifts for all the measurements divided by the number of measurements.

surements suggest a first power dependence. As a result, we conclude that the number of traps is proportional to the implantation energy. This leads to the conclusion that the trapping we are observing is due to implantation damage in the SiO_2 even though we have annealed our samples at temperatures of 1050°C. The dependence of the trap density on the implantation energy may be due to the role of vacancies created during the implantation process, making it possible for the Al to go into the structure substitutionally and thus act as trapping centers. The Al ions remain in these sites after the annealing process. The number of vacancies increases with increasing implantation energy and thus the number of substitutional Al atoms also increases.

The trap cross sections associated with this damage have been characterized and the predominant cross sections observed are 1.26×10^{-16} and 1.40×10^{-17} cm^2.

Acknowledgments
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