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INTER-TRAP TUNNELING IN HYDROGEN IMPLANTED n-Si/SiO_2 STRUCTURES

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Hydrogen ions with energy 800 eV and doses of 10^{13}, 10^{14} and 10^{15} cm^{-2} have been implanted in n-Si/SiO_2 structures with 150 nm thick SiO_2 layers, prepared by dry oxidation at 850 ºC. The MOS structures were investigated with high frequency (1 MHz) capacitance-voltage (C-V) and conductance-voltage (G-V) measurements, at 300 and 77 K. The fixed oxide charge density and trap energy density at the Si/SiO_2 interface were determined, and analyzed from the C-V measurements. The trap densities in the SiO_2 layers were estimated from the G-V measurements. In the accumulation mode, conduction in the structures does not depend on the temperature. Taking into account an inter-trap tunneling mechanism (electron tunneling via the nearest traps), the concentration and energy position of these traps in the SiO_2 layers have been determined.

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1. Introduction

Trap-assisted tunneling plays a dominant role in charge transfer through SiO_2 films in contemporary MOS (Metal-Oxide-Semiconductor) IC (Integrated Circuits). Because of this, the establishment of the charge transfer mechanism is an indispensable step needed for amelioration of properties of SiO_2 and other insulator films. Recently, it has been established that inter-trap tunneling takes place in p-Si/SiO_2 structures with 13.5 and 65 nm SiO_2 films subjected to hydrogen plasma treatment [1]. Hydrogen neutralizes the acceptors [2] and donors [3], and passivates deep levels in the Si energy gap [4] and Si/SiO_2 interface states [5]. On the other hand, hydrogen implantation is a source of different types of defect generation in semiconductors.

The aim of this work was to study the influence of hydrogen ion beam implantation on the electro-physical properties of SiO_2 and the Si/SiO_2 interface, and to determine the influence of the character and concentration of the defect on the inter-trap tunneling mechanism.

2. Experimental details

Float-zone grown 7.5 Ωcm n-Si wafers were dry oxidized at 850 °C. The thickness of the SiO_2 layers, 150 nm, was chosen to ensure that conduction in investigated structures would be entirely by a bulk dominated transport mechanism. The implantation energy of 0.8 keV was selected so that the maximum of hydrogen distribution profile would be in the middle of the SiO_2 layer. The hydrogen was implanted with low energy "IOSHJA" implanter at Goettingen University, with doses of 10^{13}, 10^{14}, and 10^{15} cm^{-2}. The MOS structures were investigated by current-voltage and high

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frequency (1 MHz) capacitance-voltage (C-V) and conductance-voltage (G-V) measurements, at 77 and 300 K.

3. Results and discussion

The C-V characteristics of hydrogen ion beam implanted n-Si/SiO_2 structures (at doses of 10^{13}, 10^{14}, and 10^{15} cm^{-2}), and a non-implanted reference sample, measured at 300 K, are given in fig.1. As the trap states at the Si/SiO_2 interface are donor-like below the Si midgap V_{ni} and acceptor-like above it, the fixed oxide charge density N_{ox} in SiO_2 was calculated by [6]:

$$N_{ox} = \frac{C_{ox}}{q}\left(V_{ni}^{\exp} - V_{ni}^{ideal}\right) \quad (1)$$

where C_{ox} is the oxide capacitance in the accumulation regime [F/cm^2], q is the elementary charge [C], and $V_{ni}^{\exp}$ and V_{ni}^{ideal} are the gate potentials [V] when the Fermi level is in the middle of the Si band gap in the experimental and ideal structures respectively.

The trapped charge density at the Si/SiO_2 was determined as

$$N_{it} = \frac{C_{ox}}{q}\left[\left(V_{ni}^{\exp} - V_{FB}^{\exp}\right) - \left(V_{ni}^{ideal} - V_{FB}^{ideal}\right)\right] \quad (2)$$

The interface state energy density D_{it} was given by

$$D_{it} = \frac{N_{it}}{\psi_{s,ni}} \quad (3)$$

where $\psi_{s.ni}$ is the surface potential when the Fermi level is in the middle of the Si band gap.

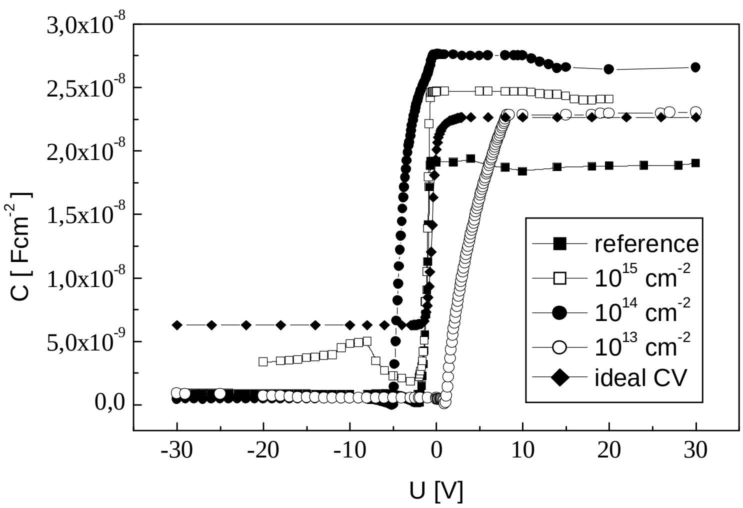

Fig. 1. C-V characteristics of n-Si/SiO_2 structures, measured at 300 K.

In Fig. 1, the C-V curves for the depletion regions of the hydrogen implanted (dose 10^{15} cm^{-2}) sample, the reference sample, and the ideal structure coincide. The C-V plots for samples with doses of 10^{13} and 10^{14} cm^{-2} are shifted toward positive and negative voltages respectively, which means that fixed negative and positive oxide charges with densities of 10^{11} cm^{-2} are created in the oxide volume for both implanted doses. These observations indicated that during ion beam implantation, defects with different natures are created in Si/SiO_2 structures. At the highest dose of 10^{15} cm^{-2}, the implanted hydrogen passivates the negative and positive defects in these structures.

The shift of the measured C-V characteristics of the same structures at 77 K is greater than at 300 K. The calculated values of N_{ox}, N_{it}, and D_{it} at 300 and 77 K are given in Table 1.

Table 1.

T [K]	Sample [cm^{-2}]	N_{ox} [cm^{-2}]	N_{it} [cm^{-2}]	D_{it} [$eV^{-1}cm^{-2}$]
300	Reference	1.99×10^{10}	3.7×10^{10}	1.29×10^{11}
	10^{15}	3.2×10^{10}	3.7×10^{10}	1.29×10^{11}
	10^{14}	4.32×10^{11}	2.36×10^{10}	8.3×10^{10}
	10^{13}	4.41×10^{11}	2.17×10^{11}	7.63×10^{11}
77	10^{15}	8.6×10^{11}	1.6×10^{11}	3.04×10^{11}
	10^{14}	1.32×10^{12}	4.51×10^{11}	8.56×10^{11}

The G-V characteristics of the samples at 300 K are shown in Fig. 2. In the accumulation mode, the conductance is independent of the applied bias voltage. These results point out that the conduction mechanism is connected with the trapping and emission of electrons by the traps in the SiO_2 layers. Confirmation of this is that the capacitances of the implanted samples in accumulation are higher than those of the reference sample. Therefore, the additional capacitance ΔC is connected to the trap charging and emission in the bulk oxide.

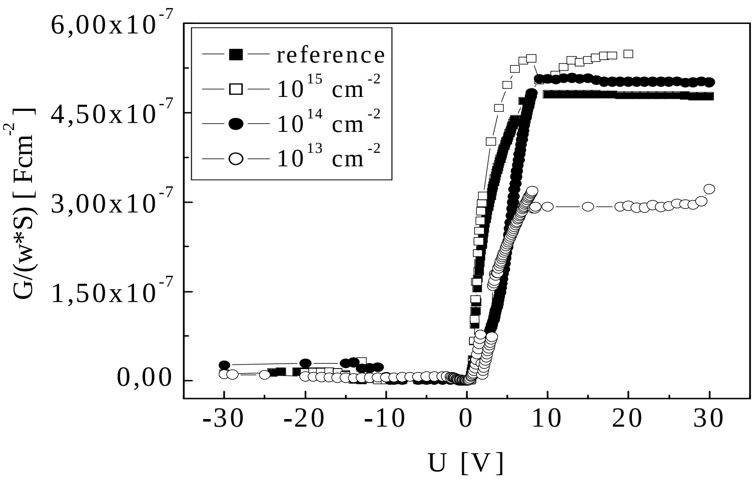

Fig. 2. G-V characteristics of n-Si/SiO_2 structures, measured at 300 K.

In these circumstances, the measured admittance in the Si/SiO_2 structure is

$$\gamma = j\omega C_{ox} + \frac{1}{R_t + \frac{1}{j\omega C_t}} \qquad (4)$$

where R_t and C_t are the equivalent resistance and capacitance of traps in the SiO_2 layers.

Transforming (4) to

$$\gamma = j\omega\left(C_{ox} + \frac{1}{1+\omega^2 R_t^2 C_t^2} \right) + \frac{C_t^2 \omega^2 R_t}{1+\omega^2 \Delta C_t^2 R_t^2} \qquad (5)$$

one may obtain the relations

$$\Delta C_t = \frac{C_t}{1+\omega^2 R_t^2 C_t^2} \quad (6)$$

and

$$\frac{G}{\omega} = \frac{C_t^2 \omega R_t}{1+\omega^2 R_t^2 C_t^2}\ , \quad (7)$$

where G is the equivalent measured conductance of the same traps.

By using the experimental values of the additional capacitance ΔC and the conductance in the accumulation region of the admittance measurements, one can calculate the $\omega R_t C_t$ and C_t values using (6) and (7). The equivalent trap density N_t^* was determined by dividing C_t by the elementary charge. The trap energy density N_t in the SiO_2 was estimated by dividing N_t^* by the layer thickness. The ΔC, G/ω, $\omega R_t C_t$, C_t, N_t^*, and N_t values are given in Table 2. The N_t values increased with the hydrogen-implantation dose. The values of N_t, in the range 1-2.5 × 10^{19} $cm^{-3}V^{-1}$, are typical for amorphous materials.

From the I-V characteristics at 300 and 77 K, one may make the conclusion that tunneling type conduction appears in the SiO_2 layer in the accumulation regime. By using an expression for inter-trap tunneling [1], the values of the distance between the nearest traps, w, and the energy position of the dominant traps responsible for inter-trap tunneling, $q\varphi_B$, have been calculated. These are 5.1 × 10^{-7} and 5.28 × 10^{-7} cm for w, and 0.57 and 0.64 eV for $q\varphi_B$, at 300 and 77 K respectively.

Table 2.

Sample $[cm^{-2}]$	ΔC $[Fcm^{-2}]$	G/ω $[Fcm^{-2}]$	$\omega R_t C_t$	C_t $[Fcm^{-2}]$	N_t^* $[eV^{-1}cm^{-2}]$	N_t $[cm^{-3}eV^{-1}]$
10^{15}	5.78×10^{-9}	5.43×10^{-7}	93.94	5×10^{-5}	3.18×10^{14}	2.65×10^{19}
10^{14}	7.86×10^{-9}	5.01×10^{-7}	57.06	3.19×10^{-5}	1.99×10^{14}	1.6×10^{19}
10^{13}	4.16×10^{-9}	2.9×10^{-7}	69.79	2.02×10^{-5}	1.26×10^{14}	1.05×10^{19}

4. Conclusions

In Si/SiO_2 structures, hydrogen ion beam implantation introduces defects with both positive and negative charge, and passivates defects in the bulk oxide and at the Si/SiO_2 interface. Defect generation prevails in structures implanted with doses of 10^{13} and 10^{14} cm^{-2}, and defect passivation is observed in structures with a dose of 10^{15} cm^{-2}. Hydrogen implantation generates defects with bulk energy densities of the order of 10^{19} $cm^{-3}eV^{-1}$. This density increases with the implanted dose.

In some of the investigated structures, trap-assisted tunneling is observed. The tunneling conductance is explained by an inter-trap tunneling mechanism. In the SiO_2, the traps responsible for this tunneling have an energy position 0.6 eV from the conduction band, and a concentration of the order of 7 × 10^{18} cm^{-3}.

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