Comparison of Electrical Properties of Silicon-on-Insulator Structures Fabricated with Use of Hydrogen Slicing and BESOI

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The top silicon layers and the bonded Si/SiO$_2$ interfaces in silicon-on-insulator (SOI) structures fabricated by (*i*) wafer bonding and hydrogen slicing, and (*ii*) by wafer bonding and chemical mechanical thinning (back-etch SOI, BESOI) were investigated and compared by charge deep-level transient spectroscopy. The hydrogen slicing was provided by hydrogen implantation into one of the bonded wafers and led to the high hydrogen concentration during SOI fabrication. Hydrogen presented in SOI during the fabrication process partially neutralizes the traps at the Si/thermal SiO$_2$ interface, and completely neutralizes shallow acceptors and contamination with deep levels in the top silicon layer.
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The conventional Si/SiO$_2$ interface prepared by thermal oxidation of silicon has a transition SiO$_x$ layer 2 nm thick.[1] It is, namely, the transition SiO$_x$ layer that determines the spectrum of interface traps.[2] Recently, a new method to create the Si/SiO$_2$ interface was developed. It is bonding of a silicon wafer with an oxidized one.[3] Bonding technology is now a promising way to create new structures for microelectronics.[3,4] Particularly, different silicon -on-insulator (SOI) structures are fabricated with use of bonding technology [for example, Smart-Cut technology[5] and back-etch SOI (BESOI[6])]. Recently, we showed that the spectrum of traps at a bonded Si/SiO$_2$ interface substantially differs from that at an Si/SiO$_2$ interface prepared by thermal oxidation.[7,8] This difference was attributed to the absence of the transition SiO$_x$ layer at the bonded interface or/and intense neutralization of traps by hydrogen due to utilization of hydrogen slicing technology (hydrogen implantation in one of the bonded wafers). The concentration of hydrogen present in SOI during fabrication can be lowered if one uses BESOI technology.[6] In this case we did not use hydrogen implantation, and a thinning of the top silicon layer was performed with polishing and etching.

The aim of this study was to compare interface traps and centers with deep and shallow levels in the top silicon layers of two different SOI types: (*i*) structures prepared by hydrogen slicing,[7,8] and (*ii*) BESOI structure.[6] The final heat-treatment of both SOI was annealing at high temperature (~1100°C). The result was that hydrogen concentration was decreased dramatically and became lower than the sensitivity of secondary-ion mass spectroscopy (SIMS).[9] Introduction of shallow acceptors, centers with deep levels, and higher density of the interface traps was observed in BESOI structures. A high concentration of hydrogen in the first type of SOI leads to neutralization of all contamination and a decrease in interface density.

Experimental and Results

To fabricate the SOI structures, Czochralski (Si-CZ) and float zone (Si-FZ) grown silicon wafers with n-type conductivity were used. SOI structures fabricated by hydrogen slicing were marked as SOI-A. The BESOI structures were marked as SOI-B. The type of initial silicon (FZ or CZ) was added to the SOI designation. Both SOI-A and SOI-B had high-temperature (1100°C) annealing in nitrogen ambient as a final step of SOI fabrication. The bonded Si/SiO$_2$ interface was placed in our structures between the top silicon layer and buried oxide. The top silicon layer for SOI-A structure was not polished after the fabrication procedure because SOI structures with a thicker top layer were more suitable for electrical measurements. The parameters of SOI investigated are presented in Table I. The concentrations of electrons in the top silicon layer and

in the substrate were found from high-frequency capacitance-voltage (C-V) measurements. The measurements were carried out on the vertical capacitance mesa structures. The aluminum contacts were fabricated by thermal evaporation of Al onto the top silicon layer and substrate. A typical area of the mesa structures ranged from 0.5 to 1 mm^2. The increase in the electron concentrations observed in the top silicon layer of the investigated SOI (Table I) is connected with formation of the shallow donors during fabrication.[9]

The experimental methods were C-V measurements, performed at a 1 MHz frequency, and charge deep-level transient spectroscopy (Q-DLTS) measurements. Q-DLTS, an alternative to the conventional DLTS, is based on registering charge transients after bias-voltage switches; it offers some advantages over DLTS when applied to metal-oxide-semiconductor (MOS) structures. The operating frequency of the Q-DLTS spectrometer was 1 kHz. The time window was varied in the range from 1×10^{-4} to 2×10^{-3} s, and the filling-pulse duration was 2×10^{-3} s.

In the Q-DLTS study, we dealt with intervals of bias voltages, which corresponded to a depletion regime at the bonded interface and to accumulation at the buried oxide/substrate interface. For each SOI structure, the above interval was determined individually by measuring its high-frequency C-V characteristics. By switching the bias voltage within this interval, we could recharge interface states at the bonded (top silicon/buried oxide) interface and "bulk" traps in the top silicon layer.

To find, from measured Q-DLTS spectra, the energy distribution of interface states at each Si/SiO$_2$ interface, we used a method previously described elsewhere.[7,8] In this method, the energy levels contributing predominantly to the Q-DLTS signal at a current temperature and chosen time window were calculated from the equation $E_c - E = kT \ln(\sigma v_T N_c \tau)$, where E is the energy level, k is the Boltzmann constant, σ is the capture cross section of the level, v_T is the thermal velocity of free carriers, N_c is the density of states in the conduction band of the semiconductor, and τ is the time window of the Q-DLTS spectrometer. This approach requires invoking a certain value of the capture cross section for the traps, which could be independently evaluated from Q-DLTS spectra. We have analyzed DLTS spectra measured with relatively low filling-pulse amplitudes and described DLTS peaks with the well-known equation for an exponential emission of charge carriers from deep centers with fixed E and σ. The obtained σ value is used for the above calculation.

We tried to create SOI structures with n-type conductivity in the top silicon layer and the substrate. n-Type conductivity in all investigated SOI allows us to obtain information about levels in the upper half of a forbidden band and to compare results for different SOI. If initial silicon wafers for SOI-A have n-type conductivity, the final SOI structures also have n-type conductivity in the top silicon layer and substrate (Table I). The situation is changed for SOI-B. The main part of mesa structures have p-type conductivity in the top silicon layer (see Table I) and only some mesa structures still keep n-type conductivity. This effect corresponds to the well-known ef-

Table I. Parameters of SOI structures. $N_{p,n}$ is hole or electron concentration.

SOI	Thickness of top Si layer (μm)	Thickness of BOX (μm)	$N_{p,n}$ in the top Si layer (cm^{-3})	N_n in the initial Si and substrate (cm^{-3})
SOI-ACZ	0.5	0.4	$N_n = 5.0 \times 10^{15}$	1×10^{15}
SOI-AFZ	0.64	0.4	$N_n = 4.7 \times 10^{15}$	8×10^{13}
SOI-BCZ	5-7	0.4	$N_n = 3.9 \times 10^{15}$ to $N_p = 10^{13}$ to 10^{14}	1.5×10^{15}

fect of contaminating a layer near the interface in the directly bonded Si/Si structures with acceptors (most likely, boron and/or aluminum atoms).[10] Thus, the high hydrogen concentration in SOI-A in comparison with SOI-B provides the neutralization effect on contamination with acceptors despite the final high-temperature annealing. The meaning of the term "neutralization" is the hydrogen-related passivation effect, which is observed after high-temperature annealing.

DLTS spectra for SOI-AFZ and SOI-BCZ are presented in Fig. 1. The DLTS spectrum for SOI-AFZ demonstrates only peaks for interface states and no peaks for deep levels in the top silicon layer. DLTS spectra for SOI-ACZ show the peaks for interface states and one or two deep levels EA1 and/or EA2.[8] Parameters of levels are given in Table II. EA1 and EA2 centers are located within a layer of

0.2 μm from the surface with increase in concentration to the surface.[8] EA1 and EA2 centers most likely correspond to postimplantation defects. The lack of centers with deep levels for SOI-AFZ is most likely due to greater thickness of the top silicon layer. The maximal depth of the depleted region in SOI-AFZ was about 0.5 μm, whereas the top silicon layer was 0.64 μm thick. Low oxygen concentration also can lead to a decrease in concentration of the postimplantation defects in the near-surface layer of SOI-AFZ.

For DLTS measurements on SOI-BCZ we have chosen structures with n-type conductivity in the top silicon layer. The DLTS spectrum for SOI-BCZ (Fig. 1) demonstrates peaks connected with the interface states and four peaks which correspond to centers with deep levels in the top silicon layer (EB1-EB4, see Table II). EB1 and EB2 are unstable peaks: their concentration is decreased during multiple DLTS measurements and with time they disappear. Such peculiarities commonly correspond to alkali metals in silicon. The other two peaks EB3 and EB4 are stable and are most likely caused by some contamination of the wafer surfaces during SOI fabrication. The bonding procedure was the same for SOI-A and SOI-B. Thus, contamination introduced during fabrication and clearly observed in SOI-B is neutralized by hydrogen in SOI-A.

Figure 2 shows the energy distributions of interface states at the bonded interface SOI-A and SOI-B. The capture cross section for these interface states was estimated to be about 10^{-18} cm^2. As seen from Fig. 2, the energy distributions of interface states of SOI-ACZ and SOI-AFZ are similar. The energy distributions of interface states of SOI-BCZ are also similar to that of SOI-A, but the density of states is about one order higher (Table II). The high density of interface states in SOI-B in comparison to SOI-A allows us to state that hydrogen presented in SOI-A during fabrication causes partial neutralization of interface states in SOI-A.

Thus, high hydrogen concentration in SOI during fabrication ($\sim 2.7 \times 10^{16}$ cm^{-2} in the top silicon layer after delaminating[9]) due to hydrogen slicing technology causes neutralization of contamination in the top Si layer and partly of interfaces states at the bonded interface. As mentioned above, the final step of SOI fabrication process was annealing at 1100°C in nitrogen ambient. According to data of secondary-ion mass spectroscopy,[9] the hydrogen concentration after the annealing became below the sensitivity of technique used ($\leqslant 5 \times 10^{15}$ cm^{-2}). Nevertheless, the clearly pronounced effects of neutralization of interface states and deep levels are found. This
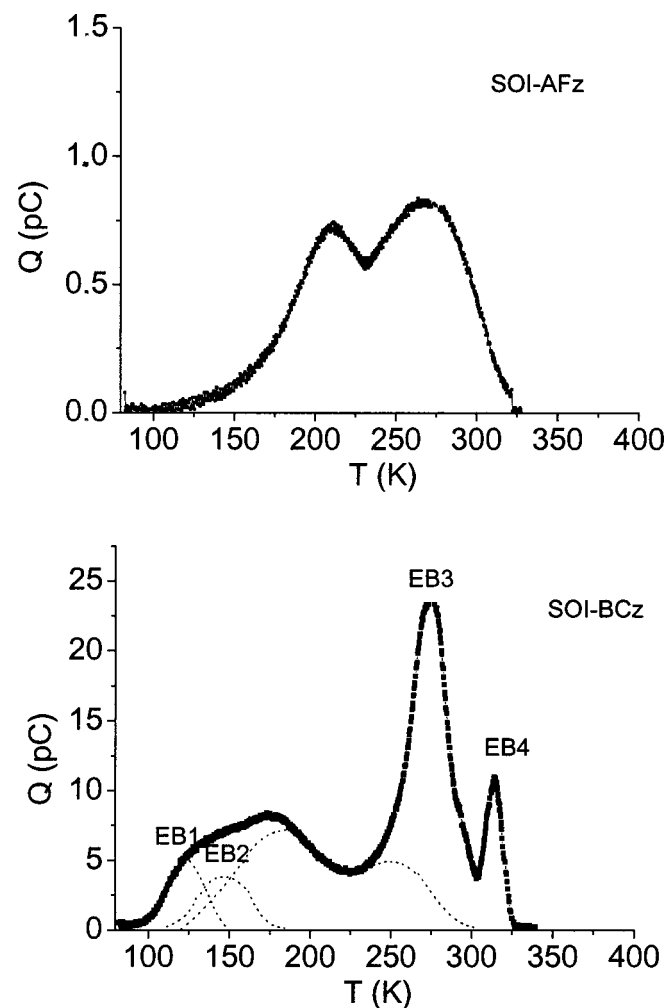

Figure 1. Q-DLTS spectra of SOI-AFZ and SOI-BCZ structures measured at bias voltage U and amplitude of the filling-pulse voltage ΔU. The indicated bias and pulse voltages were selected from C-V characteristics. For SOI-AFZ $U = 15$ V, $\Delta U = -4$ V; for SOI-BCZ $U = 9$ V, $\Delta U = -7$ V.

Table II. Parameters of centers with deep levels in the top silicon layers of SOI (energy of level, cross section, and sheet concentration) and integral density of interface states, D_{it}, at the bonded interface.

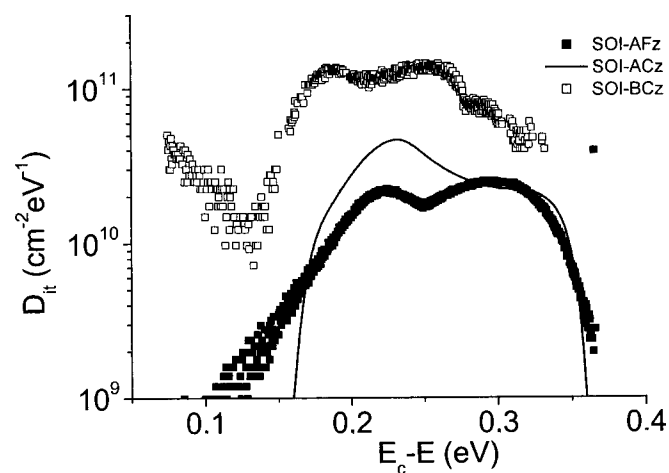| SOI	D_{it} (cm^{-2})	Parameters of deep levels		
		$E_c - E$ (eV)	σ (cm^2)	N (cm^{-2})
SOI-ACZ	5.4×10^9	EA1 = 0.38	1×10^{-15}	6.3×10^9
		EA2 = 0.58	4×10^{-14}	1.3×10^{10}
SOI-AFZ	3.5×10^9	—	—	—
SOI-BCZ	2.0×10^{10}	EB1 = 0.09	1×10^{-19}	3.4×10^{11}
		EB2 = 0.12	1×10^{-19}	2×10^{11}
		EB3 = 0.40	10^{-16}	5.3×10^{11}
		EB4 = 0.63	10^{-13}	2.5×10^{11}

Figure 2. Distribution of interface states at the top silicon layer/buried oxide interface of SOI-A and SOI-B structures.

result means that hydrogen is not completely removed during the high-temperature annealing.

Conclusion

The effects of partial neutralization of interface states at bonding Si/SiO$_2$ interface and neutralization of contamination in the top sili-

con layer was found in SOI structures fabricated by water bonding and hydrogen slicing contrary to the BESOI structure. The effect is explained by hydrogen still present in SOI despite high-temperature annealing.

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