## A "smarter-cut" approach to low temperature silicon layer transfer

Q.-Y. Tong<sup>a), b)</sup> R. Scholz, and U. Gösele<sup>b)</sup>

Max-Planck-Institute of Microstructure Physics, Weinberg 2, D-06120, Halle, Germany

T.-H. Lee, L.-J. Huang, Y.-L. Chao, and T. Y. Tan

Wafer Bonding Laboratory, School of Engineering, Duke University, Durham, NC 27708

(Received 25 August 1997; accepted for publication 3 November 1997)

Silicon wafers were first implanted at room temperature by  $B^+$  with  $5.0 \times 10^{12}$  to  $5.0 \times 10^{15}$  ions/cm<sup>2</sup> at 180 keV, and subsequently implanted by  $H_2^+$  with  $5.0 \times 10^{16}$  ions/cm<sup>2</sup> at an energy which locates the H-peak concentration in the silicon wafers at the same position as that of the implanted boron peak. Compared to the H-only implanted samples, the temperature for a B+H coimplanted silicon layer to split from its substrate after wafer bonding during a heat treatment for a given time is reduced significantly. Further reduction of the splitting temperature is accomplished by appropriate prebonding annealing of the B+H coimplanted wafers. Combination of these two effects allows the transfer of a silicon layer from a silicon wafer onto a severely thermally mismatched substrate such as quartz at a temperature as low as 200 °C. © 1998 American Institute of Physics. [S0003-6951(98)00301-5]

Wafer bonding opens up new design possibilities for the fabrication of various material combinations including single crystalline semiconductor on insulator (SOI) materials. Silicon on oxidized silicon, silicon on glass, and silicon carbide on glass or on oxidized silicon have been realized by wafer bonding of hydrogen implanted silicon wafers and layer splitting due to the formation of hydrogen implantationinduced microcracks parallel to the bonding interface (the so called "smart-cut" method).<sup>1-5</sup> However, except in the above cases where only a small difference in the thermal expansion coefficients between the silicon and the respective substrates is present, other material combinations usually suffer from excessive thermal stresses due to thermal mismatch between the silicon and the dissimilar substrate during annealing for layer splitting. For Si on Quartz (SOQ), at room temperature the thermal expansion coefficient of silicon is  $2.56 \times 10^{-6}$  °C while that of fused quartz is only 0.5  $\times 10^{-6/\circ}$ C. A bonded 4 in. standard Si/quartz pair (both of  $\sim$  525  $\mu$ m in thickness) will therefore crack if the temperature considerably exceeds 200 °C. Since the splitting temperature in the smart-cut process of silicon is typically around 500 °C.<sup>2,3</sup> the silicon wafer in the bonded Si/quartz pair has to be thinned down sufficiently ( $<150 \ \mu m$ ) to avoid cracking of the bonded pair during the silicon layer splitting process. However, by this approach involving thinning of the silicon wafers a main advantage offered by the smart-cut method is lost, namely that extensive lapping and etching to remove most of the substrate is avoided and the substrate from which the silicon layer is transferred can be reused. The normal smart-cut method is therefore virtually not applicable for realizing layer transfer onto dissimilar substrates which exhibit a large difference in thermal expansion coefficients. Therefore, an approach termed "smarter-cut"<sup>6</sup> which employs a lower temperature silicon layer splitting technology is highly desirable.

In this study, 4 in., (100), CZ, p-type, boron (B) doped

 $(\sim 7 \times 10^{15} \text{ cm}^3)$  silicon wafers covered with a 1500 Å thermal oxide layer were used.  $H_2^+$  ions were implanted at 129 keV with a dose of  $5 \times 10^{16}$  cm<sup>-2</sup>. We found that for a given annealing time the splitting temperature decreases with B doping concentration. Since the times required to form hydrogen-induced optically detectable blisters on the Himplanted unbonded silicon wafers are a measure of the required splitting time,<sup>7</sup> we determined these times for H implanted silicon wafers uniformly doped with various B concentrations as a function of temperature as shown in Fig. 1. n-type silicon with phosphorous (P) doping concentration of  $1-5 \times 10^{18}$  cm<sup>-3</sup> does not show the same effect as can also be seen from Fig. 1. The time for large area layersplitting after bonding is about ten times longer than that for the formation of optically detectable surface blisters, but the effective activation energies for the two procedures remain the same.<sup>7</sup>

Generally, for most device applications a lightly doped Si layer is required. In this case, the B doping effects can be



FIG. 1. Time required to form H implantation-induced optically detectable surface blisters on H-implanted, uniformly doped Si wafers (with phosphorous or boron concentrations as indicated) as a function of inverse absolute temperature.

<sup>&</sup>lt;sup>a)</sup>Electronic mail: material@acpub.duke.edu

<sup>&</sup>lt;sup>b)</sup>Also at Wafer Bonding Laboratory, Duke University, Durham, NC 27708.



FIG. 2. Change of temperature required to form optically detectable surface blisters in hydrogen-implanted silicon for a fixed annealing time of one minute as a function of dose of boron implanted before the hydrogen implantation. For very low boron doses their values are given individually in the graph.

realized by using a lightly doped epitaxial layer on a heavily B-doped substrate or by implanting B into a lightly doped silicon wafer, followed by annealing to activate the dopants and finally by an H implantation with the depth of its peak concentration aligned to the depth of the peak concentration of the implanted boron. In our case,  $H_2^+$  ions were implanted at 129 keV to locate the H peak at the same position as the B peak, which was implanted at 180 keV. After splitting, the boron concentration in the transferred silicon layer can be reduced to a normal level by a thermal oxidation and/or a light polishing step. Surprisingly, when the thermal treatment to electrically activate the implanted B atoms had not been performed, a much greater reduction of the temperature required to form optically detectable surface blisters for a given annealing time (termed blistering temperature) is observed, even at a B dose as low as  $5 \times 10^{12}$  cm<sup>-2</sup>. The blistering temperature decreases with B dose monotonically and quickly at low B doses. This decrease slows down at B doses beyond about  $2-5 \times 10^{14}$  cm<sup>-2</sup>. Figure 2 shows the experimental results of the change of the blistering temperature as a function of B dose when annealing time is fixed to 1 min. Compared to the silicon samples having electrically



Pre-annealing Time at 250°C (min)

FIG. 3. Time required to form optically detectable surface blisters during annealing at 200  $^{\circ}$ C on B+H coimplanted silicon samples as a function of time of preannealing at 250  $^{\circ}$ C.



FIG. 4. Cross-sectional high resolution transmission electron micrographs of (a) a B+H as-co-implanted (100) Si sample and (b) a H only as-implanted (100) Si sample. Platelets on (100), which is parallel to the surface, and on (111) planes can clearly be seen. Direction of electron beam is  $\langle 011 \rangle$ .

active B concentration of  $\sim 2 \times 10^{19}$  cm<sup>-3</sup>, the silicon samples implanted (with electrically inactive B with a dose of  $5 \times 10^{14}$  cm<sup>-2</sup> at 180 keV which generates the same B concentration of  $2 \times 10^{19}$  cm<sup>-3</sup> at the implantation peak) showed a 50% higher reduction in splitting temperature after subsequent H<sub>2</sub><sup>+</sup> implantation at 129 keV with a dose of 5  $\times 10^{16}$  cm<sup>-2</sup> to both samples.

50 Appl. Phys. Lett., Vol. 72, No. 1, 5 January 1998 Tong *et al.* Downloaded 25 Oct 2004 to 195.37.184.165. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

In order to avoid cracking of standard 4 in.-diameter bonded Si/quarts pairs a splitting temperature of  $\sim 200$  °C is required. Based on our recently developed low temperature bonding method the bonding strength of a Si/quartz pair after 200 °C annealing can reach a value of half of the silicon fracture strength.<sup>8</sup> This bonding strength is adequate to prevent blistering of the B+H implanted silicon layer at the bonding interface and to transfer the silicon layer on quartz at 200 °C. However, it will take more than 50 h to split the silicon layer at 200 °C by using the B+H coimplanted Si wafers with a B dose of  $5 \times 10^{14}$  cm<sup>-2</sup>. For a further reduction of the splitting time, preannealing of the unbonded B+H coimplanted silicon wafers was performed at 250 °C for 10 min without generation of optically detectable blisters or bubbles on the silicon surface. As can be seen from Fig. 3, the time needed at 200 °C for the generation of optically detectable surface blisters on the pre-annealed samples is only  $\sim 10\%$  of that required by silicon wafers without the preannealing. A possible increase of the surface waviness of the preannealed wafers is tolerable since the attraction force between the two wafers can elastically deform both wafers to conform to each other. The full Si layer was transferred onto a 4 in. quartz wafer at 200 °C and both the Si wafer and the quartz wafer were perfectly preserved without any cracking.

It is clear that electronic holes in the B+H coimplanted silicon wafers were not involved in lowering the splitting temperature since the implanted B had not been electrically activated. The stresses introduced by the implanted or substitutionally incorporated B atoms in silicon are not essential for the effect, because the same lowering effect as shown in Fig. 1 was also observed for H-implanted strain-free B-Ge codoped silicon. Therefore, we speculate that the implanted B atoms themselves and the defects generated by the B implantation play a crucial role in lowering the splitting temperature. It was determined by the Monte Carlo simulator TRIM-95 that each implanted B ion can generate  $\sim$  400 vacancies and silicon interstitials. In contrast to shallow donors, shallow-acceptors as well as structural defects in silicon are known to trap or getter hydrogen with a high efficiency.<sup>9</sup> It was reported that each B atom in silicon can trap a cluster of up to 12 hydrogen atoms.<sup>10</sup> The preexisting large concentration of point defects and B atoms then could give rise to a large amount of hydrogen traps. These traps may act as nucleation sites for the platelet formation in silicon. The platelets, in turn, lead to microcracks during annealing due to indiffusion of hydrogen atoms and molecular hydrogen formation and finally lead to layer splitting. Crosssectional high resolution transmission electron microscopic (HRTEM) images in Fig. 4 clearly show that the density of favorable (100) platelets parallel to the surface in B+H ascoimplanted silicon [Fig. 4(a)] is remarkably higher than that in H only as-implanted silicon samples [Fig. 4(b)]. In addition, the density of (111) microcracks inclined to the (100) surface is clearly much lower in the B+H coimplanted samples. We also found that under the same implant conditions, no significant effect can be observed if B is implanted after the H implantation.

In summary, we have found that defects generated by ion implantation in Si prior to H implantation can significantly reduce the splitting temperature of hydrogen implanted and wafer bonded silicon. Boron appears to be one of the best choices for the prebonding implantation because, in addition to generating a high number of point defects per implanted B ion, B atoms themselves may trap a cluster of hydrogen atoms and both processes are likely to assist platelet nucleation and microcrack growth. Based on these effects, a smarter-cut approach has been developed which can split a H-implanted silicon wafer at a temperature as low as 200 °C. This approach has successfully been used to transfer silicon layers from silicon wafers onto severely thermally mismatched substrates such as quartz or sapphire.

The authors are grateful for support by the German Federal Ministry of Research and Technology under Contract No. 13N6758. The grant from Intel Co. is greatly appreciated. The authors also appreciate the support by SEH Co. Assistance with TEM preparations by S. Hopfe is also appreciated.

- <sup>1</sup>M. Bruel, Electron. Lett. **31**, 1201 (1995).
- <sup>2</sup>M. Bruel, U.S. Patent No. 5,374,564 (1994).
- <sup>3</sup>M. Burel, B. Aspar, and A. Auberton-Herve, Jpn. J. Appl. Phys., Part 1 **36**, 1636 (1997).
- <sup>4</sup>L. B. Freund, Appl. Phys. Lett. 70, 3519 (1997).
- <sup>5</sup>M. K. Weldon, V. E. Marsico, Y. J. Chabal, A. Agarwal, D. J. Eaglesham, J. Sapjeta, W. L. Brown, D. C. Jacobson, Y. Caudano, S. B. Christman, and E. E. Chaban, J. Vac. Sci. Technol. B **15**, 1065 (1997).
- <sup>6</sup>Q.-Y. Tong and U. Gösele, U.S. Patent application 08/866, 951 (1997).
- <sup>7</sup>Q.-Y. Tong, K. Gutjahr, S. Hopfe, and T. H. Lee, Appl. Phys. Lett. **70**, 1390 (1997).
- <sup>8</sup>Q.-Y. Tong, G. Cha, R. Gafiteanu, and U. Gösele, J. Microelectromech. Systems **3**, 29 (1994).
- <sup>9</sup>N. M. Johnson, Phys. Rev. B **31**, 5525 (1985).
- <sup>10</sup>J. T. Borenstein, J. W. Corbett, and S. J. Pearton, J. Appl. Phys. **73**, 2751 (1993).