APPLICATION OF HYDROGEN ION BEAMS FOR SOI WAFER FORMATION*

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Abstract

The SOI wafer fabrication technique has been developed by using ion-cut process, based on proton implantation and wafer bonding techniques. It has been shown by a TRIM simulation that 65 keV proton implantation is required for a standard SOI wafer (200 nm SOI, 400 nm BOX) fabrication. In order to investigate the optimum proton dose and primary annealing condition for wafer splitting, the surface morphologic change has been observed and the microstructure evolution in the damaged layer was studied by cross-sectional TEM. As a result, effective dose is found to be in the 6~9x10^{16} H^+/cm^2 range, and the annealing at 550°C for 30 minutes is expected to be optimum for wafer splitting. Direct wafer bonding is performed by joining two wafers together after creating hydrophilic surfaces by a modified RCA cleaning integrated with megasonic cleaning, and IR inspection is followed to ensure a void free bonding. Finally, wafer splitting is accomplished by annealing at the predetermined optimum condition.

INTRODUCTION

SOI (Si-On-Insulator) describes a sandwich structure in which a monocrystalline silicon layer (device layer) is electrically isolated from the silicon substrate by an oxide layer. SOI benefits include high speed, low power consumption, low leakage current, the ability to withstand higher temperatures and radiation fields, and the integration of electrical and optical signals. So, SOI encompasses a wide array of applications, including MEMS, smart power, solar cells, and high-speed microprocessors and memories [1,2].

After SOI technology was introduced in the 1970s as a new substrate technology for military or space applications, different approaches were proposed for SOI fabrication such as SOS (Silicon-On-Sapphire), SIMOX (Separation by IMplantation of OXygen), bonded SOI, and epitaxial layer transfer [3]. At the beginning of 90's, researchers at LETI in France proposed a revolutionary technique used to transfer ultra-thin single crystal layers of wafer substrate material onto another substrate, based on ion implantation and wafer bonding as schematically presented in Fig. 1. A thermally oxidized silicon wafer is implanted with hydrogen ions, then is bonded to a bare Si wafer. Further thermal annealing will lead to the splitting of a thin Si layer from the implanted wafer and the result will be a SOI structure. The cleaved surface is finally polished by chemical mechanical polishing (CMP) and annealed to ensure a surface quality comparable to silicon prime wafers. This technique is known as ion-cut technique, and the main advantages are accurate thickness control, thickness homogeneity, good crystalline quality, low cost, high flexibility for thickness [4-6]. The flexibility of this technology extends beyond the silicon world to many applications such as SOS, Si on quartz, SiC on glass, and 3-D microstructure formations.

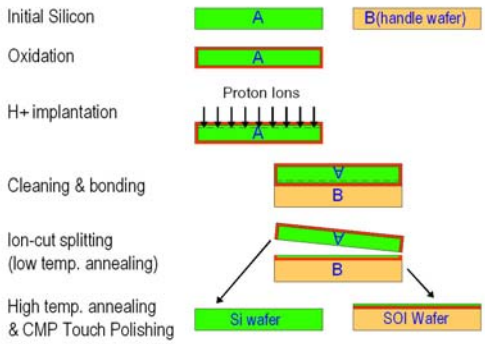

Figure 1: Schematic of the ion-cut process.

In this paper, the SOI wafer fabrication technique using ion-cut process is described. The proton irradiation mechanism related to the hydrogen ion implantation is discussed, and the effective wafer cleaning technique for direct wafer bonding wafer pairs with hydrophilic surface and the wafer splitting by thermal annealing are also discussed.

EXPERIMENTS

Hydrogen ions are implanted into p-type, 14-22 Ωcm, 100 mm silicon wafers with (100) orientation, which has been capped before implantation with a thermally grown SiO_2 layer of 400 nm thickness. This dielectric layer becomes the buried oxide (BOX) of the SOI structure. Implantation doses are varied from 3x10^{16} H^+/cm^2 to 1.2x10^{17} H^+/cm^2 to survey an optimum dose range for ion-cut splitting.

The implantation profile of hydrogen ions in a donor wafer (A in Fig. 1) with 400 nm BOX layer was simulated by TRIM (Transport of Ions in Matter) code as shown in Fig. 2. Considering the surface roughness and the silicon consumption necessary for the final polishing, 65 keV proton implantation (R_p=692nm, ΔR_p=100nm) is found to be suitable for the standard SOI structure. The normal hydrogen depth distribution is confirmed by Elastic Recoil Detection (ERD) measurement.

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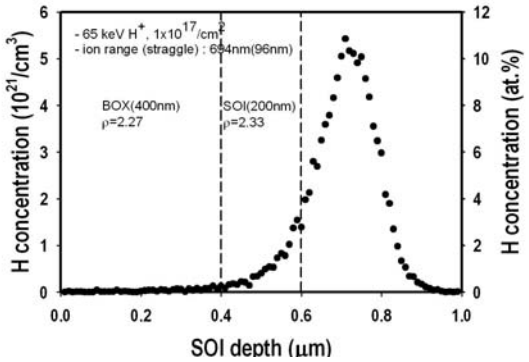

Figure 2: Schematic of the ion-cut process.

Two wafers A and B are bonded via hydrogen bonds after hydrophilic cleaning by using a SC-1 (RCA standard clean-1) and SPM steps, and wafer B plays as a stiffner in the ion-cut process and provides the bulk silicon under the BOX layer in the SOI structure. Then, two-phase heat treatment of the two bonded wafers is followed. During the first annealing (500~600°C), the implanted wafer A splits into two parts remaining a thin layer of monocrystalline silicon bonded to wafer B, and the second high temperature annealing (>1000°C) stabilizes the bonding interface.

RESULTS AND DISCUSSION

Microstructure evolution by hydrogen ion implantation and low temperature annealing

Fig. 3(a) shows a low magnification cross-section TEM (XTEM) image of the damaged layer in a bare silicon wafer before annealing. As shown in Fig. 3(b), platelet-like defects in {111} and {100} planes can be observed in the damaged layer [7]. The (111) and (100) planes are closely packed planes in silicon crystals, and defects are readily formed in these planes by the agglomeration of hydrogen atoms [8].

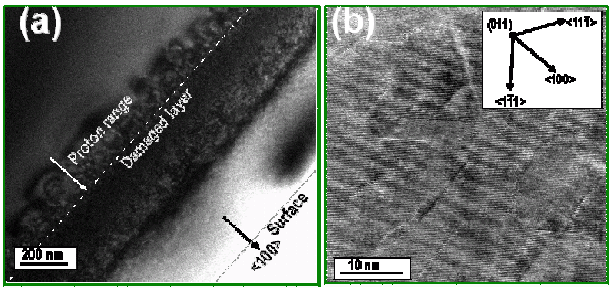

Figure 3: Schematic of the ion-cut process.

The formation of blisters is observed on the surface by the formation of bubbles in preference to platelets even without thermal treatment in the highest dose of $1.2x10^{17}$ H^+/cm^2. For limited implantation doses at low temperature, no morphological change effect is observed on the surface of as-implanted wafers, and a bonding step with other wafer is possible. At an elevated temperature (400 ~ 600°C), the mean size of the microcavities increases during annealing inducing deformations of the surface as blistering and flaking. When a handle wafer is bonded to the surface as a stiffner, this blistering phenomenon does not take place and a propagation of the cavities is observed. During annealing, microcavity size increases and an interaction between all the microcavities results in the propagation of a crack along the cavity plane and the complete separation parallel to the bonded surface. The originality of the ion-cut process is to use this propagation of cavities as a way to induce in-depth splitting over the whole wafer.

In order to determine the optimum range of implantation doses and annealing parameters, bare silicon samples implanted in the range of $3\sim9x10^{16}$ H^+/cm^2 are annealed at various temperatures (450°C ~ 650°C) for treatment times from 5 to 30 minutes. At the lowest dose of $3x10^{16}$ H^+/cm^2, no surface change is visible on the wafer surface with any annealing parameter. At the implantation doses of $6x10^{16}$ H^+/cm^2 and $9x10^{16}$ H^+/cm^2, the areal density of generated blisters (and flakes) is sufficient for ion-cut splitting, and the annealing at 550-600°C for 20-30 minutes is found to be optimum for the process.

Wafer direct bonding and SOI fabrication

Wafer cleaning is essential in ion-cut process to eliminate defects like voids in the bonding interface. Implantation step induces a considerable particle contamination and the density reaches more than 100 particles/cm^2.

The cleaning sequence for Si direct bonding starts with an SC-1 step integrated with megasonics (200 kHz, 2.4 kW), which removes particles and metallic contaminants, and ensures surface hydrophilisation with hydroxyl (-OH) surface termination. The next cleaning step is an SPM (H_2SO_4:H_2O_2=4:1) step to remove heavy organic contamination, and the particle removal efficiency reaches above 99 %.

Subsequent to the final cleaning step, the wafers are directly transferred to the bonding stage with an IR inspection system (Fig. 4). The bond is originated by pressing in the middle of one of the wafer to create an initial point of contact while two mechanical spacers keep the wafers physically separated to avoid multiple bonding waves. Upon retrieval of the spacers, a single bonding wave propagates from the center of the wafer, and a 4" wafer is bonded completely in about 8 seconds in this experiment. Fig. 5 shows a void free IR image of a directly bonded wafer pair.

Fig. 6 shows a SOI wafer fabricated by ion-cut splitting. The role of the first annealing is not only to induce the splitting but also to improve the bonding strength by the chemical reactions between silanol groups linked via hydrogen bonds. The hydroxyl groups form water molecules that in turn promote the oxidation of the bonding surfaces, creating a Si-O-Si bond as the hydrogen diffuses away. The fracture surface energy on bonded wafers is measured to be about 1.1 J/m^2 after the annealing by a razor blade test, and it is compared with the value of 0.14 J/m^2 before annealing.

Figure 4: Inside view of the wafer bonding and IR inspection system.

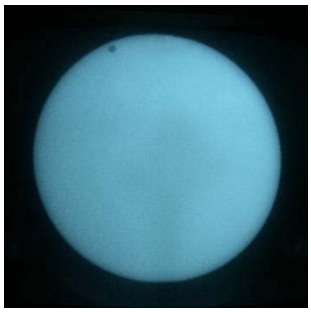

Figure 5: IR transmission image of directly bonded wafers with no void.

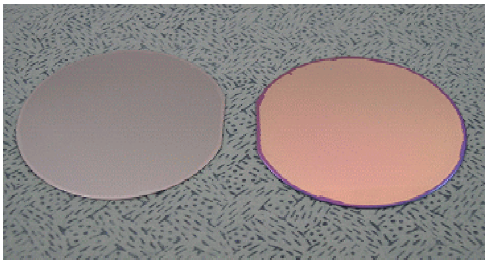

Figure 6: SOI wafer fabricated by ion-cut splitting.

Finally, high temperature annealing is performed at 1100°C in a high purity N_2 environment to create a permanent covalent bonding. Oxygen will also diffuse into the crystal lattice to create a bond interface that is not distinguishable from the rest of the silicon crystalline structure. In fact, it has been reported that at high annealing temperatures (>1000°C) the strength of the bond approaches that of silicon itself.

The micro-roughness of the splitted wafer surface is measured to be about 6.9 nm by AFM, and a final touch polishing step is required to achieve the roughness comparable to that of prime quality bulk silicon wafers.

CONCLUSIONS

In conclusion, we have successfully fabricated high-quality SOI structures using the ion-cut process based on hydrogen ion implantation and wafer direct bonding. According to TRIM simulation, a 65 keV hydrogen ion implantation is done for standard SOI wafers (200 nm SOI, 400 nm BOX) fabrication. The microstructure evolution of a hydrogen-implanted Si wafer before and after annealing was studied by XTEM. Hydrogen implantation produces a damaged layer at the projection range with plate-like defects parallel to the wafer surface. For limited implantation doses ($6\sim9\text{x}10^{16}$ H^+/cm^2) at low temperature, no morphological change effect is observed on the surface of as-implanted wafers. The surface contamination induced by ion implantation is removed by a SC-1 cleaning integrated with megasonic agitation and SPM cleaning. With a directly bonded stiffner, microcavities grow during splitting annealing at 550°C for 30 minutes and an interaction between all the microcavities results in the propagation of a crack along the cavity plane and the complete separation parallel to the bonded surface, leading to a SOI structure successfully.

ACKNOWLEDGEMENT

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