

The Generic Nature of the Smart-Cut® Process for Thin Film Transfer

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The Smart-Cut® process, based on ion implantation (hydrogen, helium) and wafer bonding, appears more and more as a generic process. The first part of the paper is dedicated to the specific case of thermally-induced splitting. Cavity growth by the Ostwald ripening mechanism and crack propagation are responsible for thermally-induced splitting. In this case, the splitting kinetics are controlled by hydrogen diffusion. In the second part, the latest results concerning new structures are presented.

Key words: Wafer bonding, ion implantation, SOI, Si, LiNbO₃

INTRODUCTION

The Smart-Cut® process is based on ion implantation and wafer bonding.¹ Ion implantation (hydrogen, helium) induces formation of an in-depth weakened layer, located at the mean ion penetration depth, which leads to delamination of a thin film from a thick substrate. Wafer bonding and layer transfer enable different materials to be associated to form multi-layer substrates. This is particularly advantageous when a thin monocrystalline layer is required on a support which does not allow epitaxy of this layer. This process, first developed to obtain silicon-on-insulator (SOI) materials, is now an industrial process which provides high quality materials in large quantities. As it enables a large number of material combinations to be achieved, numerous studies are under way to develop new structures using this process.²⁻⁶ Several of these new structures combining different materials and different bonding layers will be presented.

The Smart-Cut process can be schematically described by the following steps to obtain SOI wafers (Fig. 1):

1. Hydrogen is implanted in a substrate A. This step induces formation of an in-depth weakened layer.

2. Substrate A is bonded to a support B by wafer bonding.
3. A splitting step, which takes place along the in-depth weakened layer, gives rise to transfer of a thin layer from the substrate A onto the support B.
4. A final treatment can be performed to remove the rough surface left after splitting.

This process has several advantages from both the technical and economic points of view.⁷ Among these, the possibility of transferring thin layers of very good thickness homogeneity and with a high crystalline quality onto different materials deserves to be highlighted. From an economic point of view, the possibility of reusing the remainder of the implanted substrate helps in reducing costs.

STATUS—PHYSICAL MECHANISMS INVOLVED IN SPLITTING

The Smart-Cut process is a generic process working on different materials but, up to now, the most advanced studies have been carried out on silicon. In the following, some basic mechanisms involved in splitting of silicon wafers subjected to hydrogen implantation and thermal treatment will be presented.

Effect of Hydrogen Implantation in Silicon

As-implanted wafers have been studied by TEM

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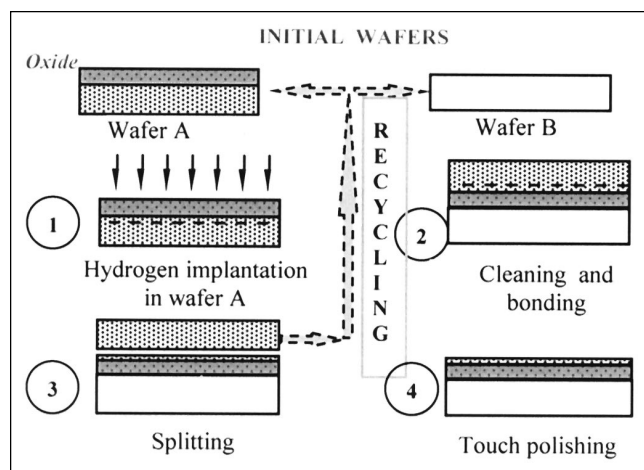


Fig. 1. Schematic description of the Smart-Cut® process, used to obtain SOI wafers.

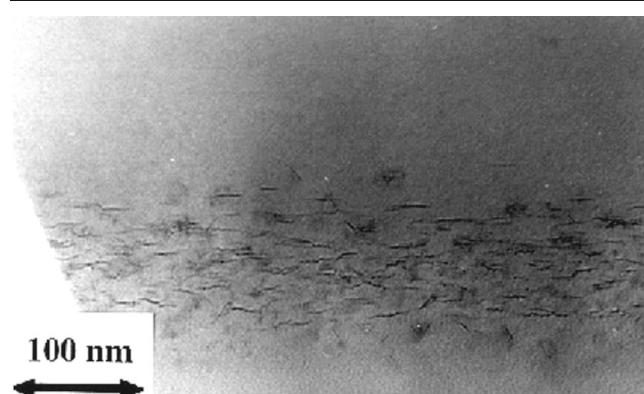


Fig. 2. Typical cavities observed by TEM.

and infrared absorption spectroscopy.^{8,9} After implantation of hydrogen doses in the range of a few $10^{16}\text{H}^+/\text{cm}^2$ to $10^{17}\text{H}^+/\text{cm}^2$, no defect is detected close to the silicon surface, but platelets or microcavities confined around the maximum hydrogen concentration depth (R_p) can be found. In (100) wafers, the platelets lie essentially on the (100) planes parallel to the surface and to a lesser extent on the (111) planes, which are energetically the most favorable. For a $6 \times 10^{16}\text{H}^+/\text{cm}^2$ implantation dose, the platelets are about 10 nm large and 1 or 2 atomic planes thick. Furthermore, infrared absorption spectroscopy indicates that, after hydrogen implantation, hydrogen is bound to silicon mainly as monohydride species, in different sites.¹⁰ The size and density of the microcavities depend on the implantation conditions and can vary from small platelets up to microsplittings. In some extreme cases, these microsplittings, located around R_p , can have a size of several microns and even lead to formation of blisters optically visible at the wafer surface. For example, a high dose hydrogen implantation of $2 \times 10^{17}\text{H}^+/\text{cm}^2$ leads to formation of blisters due to microsplittings.

Thermal Treatment of Hydrogen Implanted Silicon Wafers

After hydrogen implantation in the range of a few

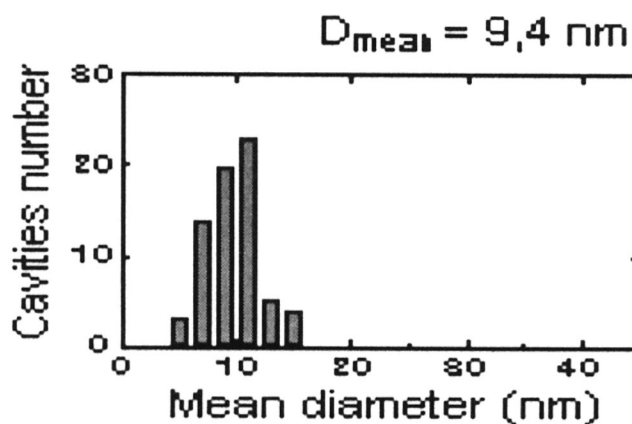


Fig. 3. Typical distribution of the size of cavities.

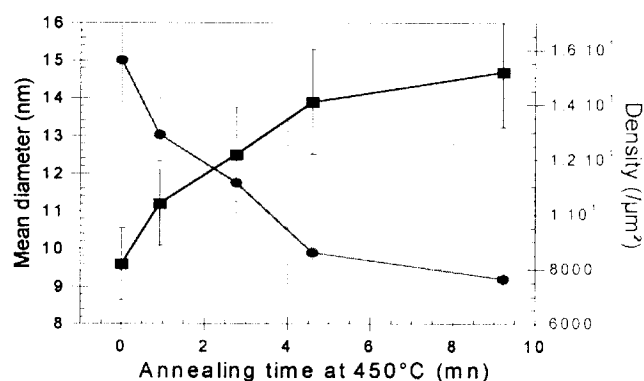


Fig. 4. Evolution of the size and density of cavities during the first annealing step.

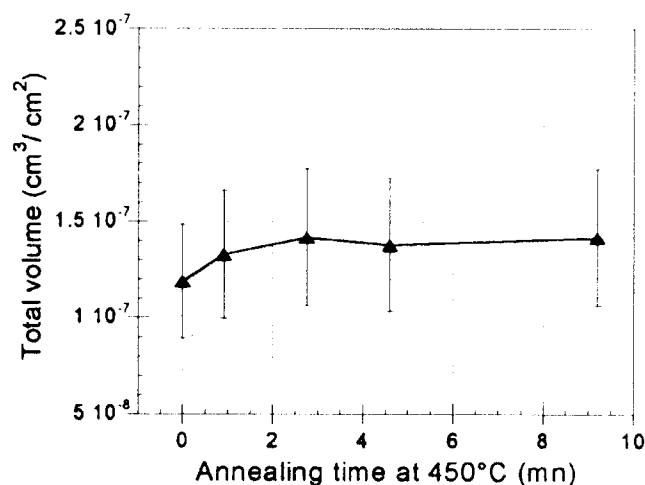


Fig. 5. Evolution of the total volume of the (100) cavities.

$10^{16}\text{H}^+/\text{cm}^2$ to $10^{17}\text{H}^+/\text{cm}^2$, thermal treatment induces the growth of microcavities. This growth can lead to the formation of micro-cracks and results in microsplittings. A quantitative study of the thermal evolution of these platelets requires the use of specific conditions when imaging by transmission electron microscopy (TEM)¹¹ (Fig. 2), so that the size-distribution, density, and overall volume occupied by the cavities can be measured for different annealing conditions (Figs. 3–5). Statistical analysis of such popu-

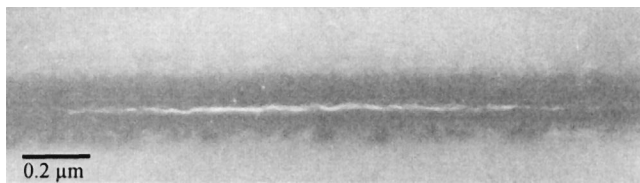


Fig. 6. Microcracks located around Rp.

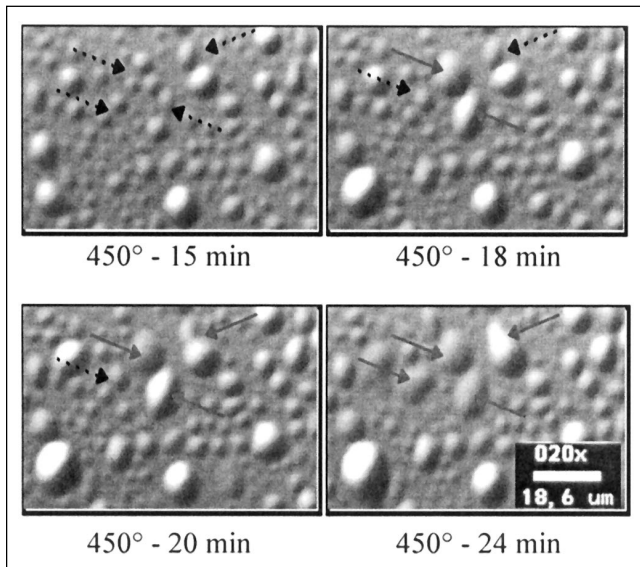


Fig. 7. Blister coalescence with annealing time (optical observation).

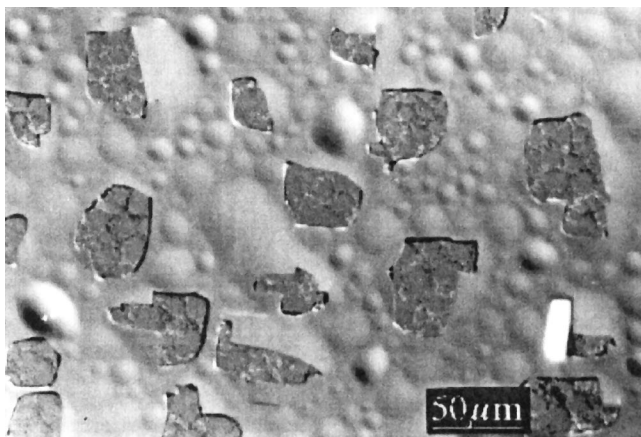


Fig. 8. Exploded blisters showing interaction between microsplittings (SEM observation).

lations can only be performed through a combination of “2 beam” and “off Bragg, strongly defocused” imaging. A study performed in the case of $6 \times 10^{16} \text{H}^+/\text{cm}^2$ implanted at around 70 keV has shown that the first steps of thermal treatment lead to growth in size of the (100) microcavities parallel to the surface while their density decreases, as expected for an Ostwald ripening type growth mechanism (Fig. 4). It should be noted that the total volume occupied by the (100) cavities remains quite constant during the same phase of the thermal treatment (Fig. 5), i.e., this process is conservative as already observed in a previous study performed after a $3 \times 10^{16} \text{H}^+/\text{cm}^2$ implantation.⁸ Such

a coarsening involves H diffusion from small platelets to larger ones. The same study was carried out for the (111) cavities and showed that these cavities do not grow during annealing and thus do not play a significant role in splitting.

However, in the case of $6 \times 10^{16} \text{H}^+/\text{cm}^2$, for a longer annealing time, some microcracks or microsplittings appear in the implanted zone (Fig. 6). These microsplittings can develop up to such a size that blisters are optically visible on the surface of the implanted wafer when no stiffener is present on this surface. A detailed study of the evolution of such blisters during annealing is presented in Fig. 7, in which the coalescence of the blisters can be observed. This means that cavities can grow due to a coalescence phenomenon involving crack propagation. This is consistent with the observations of exploded blisters by scanning electron microscopy (SEM) (Fig. 8). These observations suggest that interaction between a large number of microcracks is at the origin of this blistering and local exfoliation. Thus, in addition to cavity growth due to an Ostwald ripening type mechanism, a crack propagation mechanism is involved in the expansion of microcavities leading to splitting. Such a mechanism can be understood through energetic considerations. This approach was first proposed by Griffith and has already been used to discuss some mechanisms involved in wafer splitting.^{9,12–14}

It leads to the conclusion that crack propagation depends directly on the total applied stress which can be identified as pulling, shearing, or tearing stresses or pressure effect on the cavities, or even the applied stress linked to bonding.

The presence of the pressure in the microsplittings and, therefore, in the microcavities, was highlighted by an analysis of the blisters by Raman spectroscopy. This study clearly indicates that molecular hydrogen is present inside the blisters (Fig. 9).

To summarize, all the studies by TEM, SEM, and optical observations evidence the driving forces for cavity growth and microsplitting propagation: an Ostwald ripening mechanism takes place to reduce surface energy, and a cavity growth involving crack propagation occurs due to the total stress applied to the cavities.

Splitting Kinetics

When the implanted wafer is bonded to a stiffener, splitting can be obtained on the full wafer. The annealing time necessary for splitting was measured as a function of the annealing temperature to determine the limiting phenomenon. For this study, the implantation dose is chosen at about $6 \times 10^{16} \text{H}^+/\text{cm}^2$ for an implantation energy around 70 keV on a p-type silicon wafer ($5 \times 10^{14} \text{B}/\text{cm}^3$). Representing the splitting time as a function of the annealing temperature on an Arrhenius-type plot shows two activation energies, depending on the temperature range (Fig. 10).

At high temperatures, a splitting activation energy of about 0.5 eV is found. As suggested by the results on hydrogen diffusion in silicon, first obtained by Van

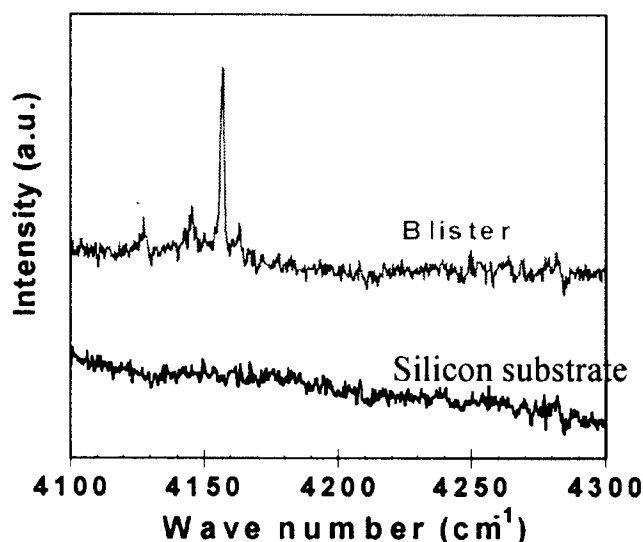


Fig. 9. Blisters analysis by Raman spectroscopy (vibrational Raman line of molecular Hydrogen is around 4158 cm^{-1}).

Wieringen and Warmoltz,¹⁵ we associated this low activation energy to free atomic hydrogen diffusion in silicon (~ 0.48 eV).

At low temperatures, the splitting activation energy is about 2.2 eV: hydrogen diffusion is still expected to occur, but under these conditions linked to a trapping-detrapping phenomenon due to the trap efficiency in this temperature range.^{8,9} In this case, this activation energy can, therefore, be associated to the sum of the free atomic hydrogen diffusion energy of 0.48 eV (E_{Hdiff}) and a binding energy of about 1.6–1.8 eV. This is consistent with published binding energies of hydrogenated complexes in silicon.¹⁶ In this case, splitting is controlled by hydrogen diffusion limited by the trapping phenomenon.

This effect is confirmed by the activation energies found for high implanted doses $10^{17}\text{H}^+/\text{cm}^2$ or high doping level ($[B] = 10^{19}/\text{cm}^3$).⁸ In both cases, the activation energies at low temperature (respectively, 1.2 eV and 1.1 eV) differ from the previous case (2.2 eV) evidencing a change in the nature of the trapping sites involved.

It should be noted that a large number of experimental points are necessary to plot the splitting kinetics accurately, especially at low temperatures. The use of only three points can lead to a doubtful activation energy.

NEW DEVELOPMENTS

Silicon On Insulator Wafers

The major application of this process is at present fabrication SOI wafers. The use of SOI wafers instead of silicon wafers to achieve integrated circuits provides some advantages which are very interesting for low voltage or low power consumption applications. The Smart-Cut process is well suited to obtaining SOI wafers, especially for very thin top silicon layers $< 1.5\ \mu\text{m}$. This process allows a large flexibility in layer thickness with a very high silicon thickness

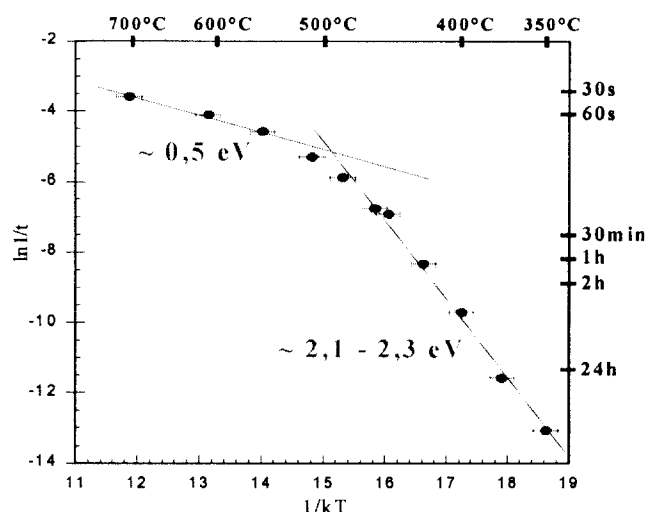


Fig. 10. Time necessary to obtain transfer of a thin layer as a function of annealing temperature. ($6 \times 10^{16}\text{H}^+/\text{cm}^2$ –70 keV on a p-type [$5 \times 10^{14}\text{B}/\text{cm}^3$] silicon wafer).

homogeneity (< 10 nm for 200 mm wafers). Moreover, we demonstrated that the roughness just after splitting is greatly dependent on the implantation conditions (Fig. 11). For example, this roughness, measured by atomic force microscopy (AFM), which presents a Rms value of 11 nm for $5 \times 10^{16}\text{H}^+/\text{cm}^2$ at 95 keV can be divided by a factor of 2 (Rms value of about 5 nm) simply by changing the implantation parameters slightly ($10^{17}\text{H}^+/\text{cm}^2$ at 75 keV).

Furthermore, this technique enabled us to obtain very good crystalline quality of the top silicon layer. For example, the results obtained on new generation SOI indicate a density of Secco defects of a few hundred defects/ cm^2 for a remaining silicon thickness after etching as thin as 30 nm.¹⁷ In parallel, the density of hydrofluoric acid (HF) defects is in the $1\ \text{cm}^{-2}$ range for SOI made from Czochralski (CZ) wafers and lower than $0.1\ \text{cm}^{-2}$ when SOI are made from initial low Cop wafers. These HF defects are essentially induced by grown-in defects present in the initial silicon wafer used to obtain the top silicon layer. The interfaces of the SOI structure are very sharp as can be seen by TEM (Fig. 12). All these results obtained on 100–200 mm SOI wafers indicate that the Smart-Cut process is well suited for achieving very high quality SOI wafers.

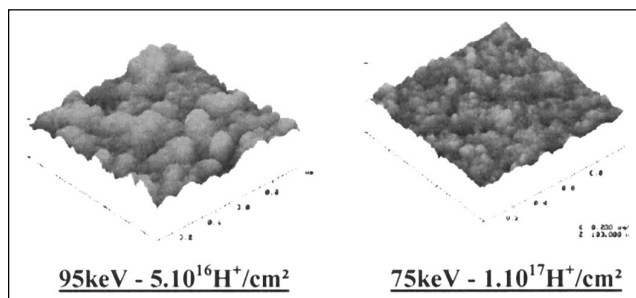


Fig. 11. Influence of implantation parameters on surface roughness after splitting.

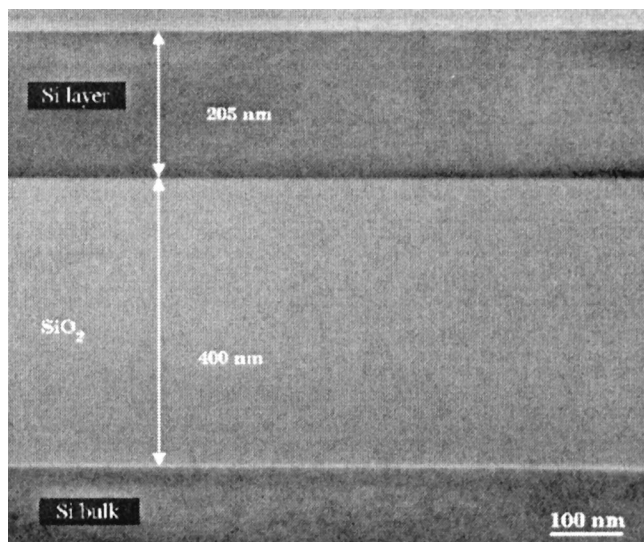


Fig. 12. TEM cross-section of a SOI wafer.

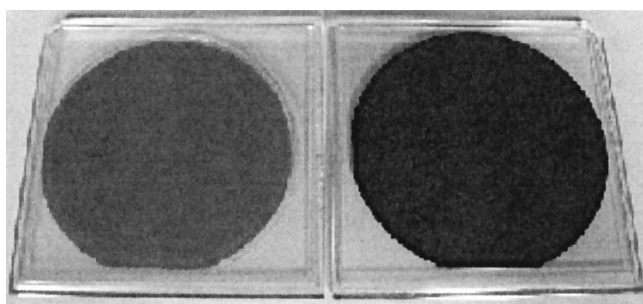


Fig. 13. Transfer of silicon on fused silica and seed wafer after transfer (100 mm wafers).

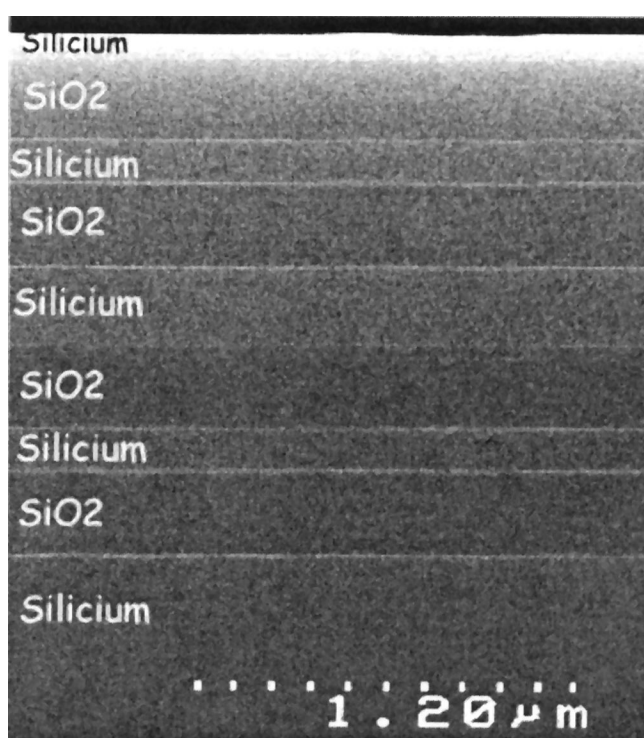


Fig. 14. SEM view of multiple SOI layer stack.

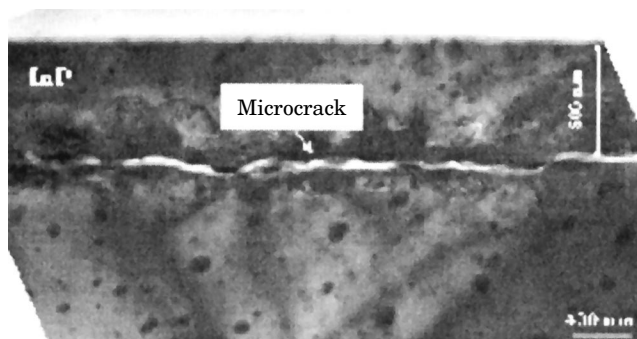
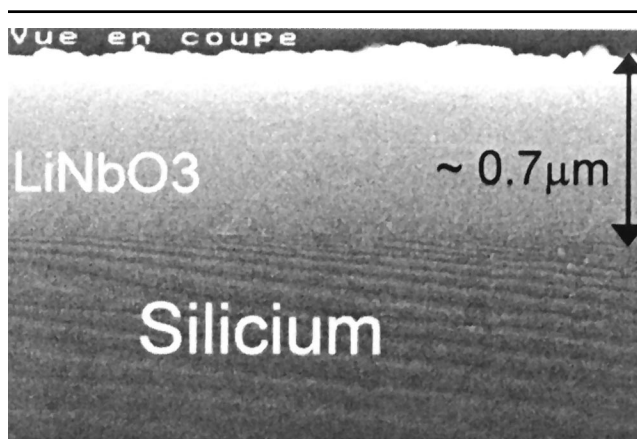


Fig. 15. XTEM observation of microcracks in semi-insulating InP (100) after H implantation and annealing at 400°C.

Fig. 16. Thin Film of LiNbO₃ transferred onto silicon wafer.

New Structures

Insulating Bonding Layer

The possibility of transferring thin silicon films using Si₃N₄ layers was demonstrated. These layers present some advantages such as a thermal conductivity thirty times higher than SiO₂ layers and good compatibility with GaAs material. Moreover, bonding of a Si₃N₄ layer onto a SiO₂ layer has also been performed giving rise to a new SOI structure.

Insulating Substrate

For some applications, it can be interesting to obtain thin silicon films on fused silica. So, we demonstrated that the Smart-Cut process can lead to transfer of a thin film and reclaiming of the seed substrate even for structures where the two materials exhibit different thermal expansion coefficients such as silicon and fused silica (Fig. 13).

Conductive Bonding Layers

For some other applications, a low-resistance electrical contact between layer and substrate is required. Recently, we demonstrated that Smart-Cut is compatible with metallic bonding.¹⁸ Palladium was used to obtain metallic bonding because it readily reacts with Si, GaAs, InP at low temperatures (<200°C).

Complex Structures

The flexibility of this process can be used to realize

complex structures. For example, this layer transfer process can be repeated several times on a same structure. Realizing multiple SOI layers based on a layer transfer process can be achieved in many different ways: repeating a single layer transfer several times onto a same wafer, transferring SOI layers stacks already formed onto a single substrate or a SOI wafer. So, multiple SOI layers stacks can be easily performed thanks to Smart-Cut technology (Fig. 14).¹⁹

Transfer of Different Materials

Many materials can be delaminated using the Smart-Cut process.

Silicon Carbide

Transfer of SiC thin films onto low-cost, large-size substrates such as silicon or polycrystalline SiC wafers is interesting for development of high-temperature, high-power, high-frequency and optoelectronic SiC/GaN based devices.

The Smart-Cut process enables transfer of high-quality monocrystalline thin films onto a supporting wafer²⁰ as well as reclaiming of the delaminated monocrystalline SiC wafer which can be reused for the same purpose. As for the case of silicon, hydrogen-induced microcavity shapes, densities and evolution have been studied by TEM. Grisolia et al. have reported similarities between silicon and silicon carbide.²¹

Moreover, the kinetics of splitting in 4H SiC have been studied and exhibit the same behavior as that obtained for splitting of silicon.⁹ For some applications, it is interesting to have a support compatible with high-temperature epitaxy. With this end in view, we recently transferred a 4H SiC film onto a polycrystalline SiC support via an Si₃N₄ bonding layer.

Gallium Arsenide

A thin GaAs film on a silicon substrate is of great interest for fabrication of opto-electronic and microwave devices as it combines the advantages of both materials. GaAs wafers exhibit the same kind of behavior as silicon and SiC when subjected to hydrogen implantation³ (100 keV with a dose in the 5×10^{16} to $10^{17}/\text{cm}^2$ range) and annealing ($T > 200^\circ\text{C}$). The feasibility of transferring a 3-inch GaAs film onto an Si substrate using the Smart-Cut process was demonstrated. As SiO₂ layers are unstable on GaAs, a thin layer of GaAs was transferred onto silicon through Si₃N₄-SiO₂. The hydrogen implantation parameters were improved, and transfer of thin monocrystalline GaAs films onto silicon substrates could be performed at a splitting temperature of about 250°C.

Indium Phosphide

We also investigated the possibility of splitting InP to obtain a thin InP film on silicon. The potential applications are low-cost InP pseudo-substrates, integration of optical functions on silicon, and spatial solar cells. The mechanism is still the same, and we showed that after proton implantation at 100 keV energy and for doses varying from 7×10^{16} to 10^{17} H^+ /

cm², blisters occur at the InP surface after thermal treatment in a 250–400°C temperature range. The minimum temperature to obtain blisters within a reasonable time depends directly on the implanted dose. After bonding onto silicon wafers, we succeeded in transferring semi-insulating InP films and InP with various dopants (S, Sn, and Zn)⁴ (Fig. 15).

Lithium Niobate

Up to now, the Smart-Cut process has been successfully used to obtain the transfer of semi-conductor material with a cubic or hexagonal crystallographic structure. Some studies have indicated that splitting and blistering took place with more complex materials (SrTiO₃, LaAlO₃).^{6,22} At LETI, we demonstrated the possibility of transferring a thin film of LiNbO₃ onto different support using this process. For example, we successfully transferred a thin film of LiNbO₃ onto silicon wafer (Fig. 16).

CONCLUSIONS

A study of the physical mechanisms involved in thermally activated splitting, obtained after proton implantation, was carried out. The splitting appears to be linked to cavity growth by an Ostwald ripening mechanism and crack propagation due to the total stress applied to the structure. The splitting kinetics are controlled by hydrogen diffusion. Splitting was successfully performed in semiconductors such as silicon, SiC, GaAs, InP, Ge, and also in LiNbO₃. Other studies report that GaN, LaAlO₃, SrTiO₃ can also be split after hydrogen implantation. The ability to obtain thin films by means of the layer transfer process combined with specific bonding via thermally conductive or metallic layers has also been demonstrated. In this paper, we focused essentially on homogeneous thin film transfer, but previous studies have shown that this process is also compatible with patterned layers.

Based on these results, we can conclude that the Smart-Cut process really is a generic process. It allows a great deal of combinations (material and bonding layer) which open up new scope for developments.

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