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Transfer of Thin Si Layers by Cold and Thermal Ion-Cutting

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ABSTRACT

We have used the crack opening method to study the mechanical exfoliation behaviour in hydrogen implanted and bonded Cz Si. We found out that the crystal orientation and boron doping influence the temperature required for mechanical layer transfer. The boron implantation at doses $>10^{13}$ cm^{-2} reduces the annealing temperature needed for mechanical exfoliation. The boron doped epilayers followed similar exfoliation behaviour as the boron-implanted samples. No lowering of the exfoliation temperature was observed for compensated and arsenic doped Si layers. The hydrogen implantation converted silicon wafer surface from p-type to n-type. The as-transferred Si layer was also found to be n-type after annealing at 200–450°C. The p-type conductivity was restored upon annealing at around 600°C. We believe that this conductivity conversion is due to the combined effect of ion-enhanced thermal donors and the presence of H-related shallow donors in the implanted layer. The p-type conductivity is restored at higher temperatures following the dissociation of the thermal donors and the out-diffusion of hydrogen. We also report that a good quality silicon on glass layer can be obtained by the bonding and ion-cutting processes.

Keywords: wafer bonding, exfoliation, silicon-on-glass

INTRODUCTION

Plasma assisted wafer bonding and layer transfer techniques can be utilized to integrate dissimilar materials at a wafer level enabling fabrication of multilayered wafers for optimal device performance. Hydrogen implantation induced exfoliation of Si has been shown to be an effective method to transfer a thin layer of Si to another wafer [1,2]. The splitting and transfer process of the hydrogen implanted and bonded Si is generally referred to as an ion-cutting process. The exfoliation of Si can be accomplished by thermal or mechanical means. Thermal exfoliation is normally carried out at a moderately high temperature of 300–600°C, whereas mechanically induced splitting of Si can be accomplished at <250°C. These low processing temperatures are particularly attractive for materials with a large difference in the thermal expansion coefficient or with a low softening point such as glass. Besides having a low process temperature, mechanical exfoliation has the advantage of producing a smooth split surface. In mechanical layer transfer or cold ion-cutting process, the implanted and bonded wafer pair is subjected to mechanical splitting forces which initiate the fracture across the bonded wafer. The delamination of a bonded wafer pair can be carried out with a gas, fluid or solid wedge [2,3,4]. Since the fracture propagates through the weakest region of a bonded wafer pair, it is necessary to achieve high bond strength at a low temperature. If the hydrogen implanted layer is weaker than the bonded interface the fracture propagates inside or near the damage zone created by the implantation. We have investigated the influence of crystal orientation and doping on the mechanical exfoliation of Si using the crack opening method [5] and Rutherford backscattering spectrometry (RBS). We also report that low-temperature plasma enhanced wafer bonding and ion-cutting processes can be used to integrate a thin single crystalline layer of Si on a glass wafer.

EXPERIMENTAL

In this work <100>, <111> and <110> oriented Czochralski (CZ) grown p-type 100 mm Si wafers with a resistivity of 1–35 Ωcm were used as donors for layer transfer. A boron or arsenic doped epitaxial (epi) Si layer was deposited on some of the <100> donor wafers. Two different boron concentrations of the epilayers 7.6 x 10^{18} cm^{-3} and 7.83 x 10^{19} cm^{-3} were studied. The arsenic concentration was 1.1–1.2 x 10^{19} cm^{-3}. To study the effect of the electrical activity of the epilayer, a compensated sample was prepared by doping the epilayer with the same

concentration level (10^{19} cm^{-3}) of boron and arsenic. The 100 mm handle wafers were <100> oriented Si, quartz glass or alkaline earth aluminosilicate (Corning 1737F) glass wafers. The thickness of the wafers was 500–600 µm. The Si handle wafers were thermally oxidized to a thickness of 500 nm of SiO_2 to make a silicon oxide to hydrophilic Si bond (oxide/Si bond). The glass handle wafers were bonded to unoxidized donor Si wafers. The donor wafers were implanted with H_2^+ at 100 keV to a dose of 4.0×10^{16} – 5.0×10^{16} H_2/cm^2. Prior to hydrogen implantation some of the <100> donor wafers were implanted with B^+ at 175 keV to a dose ranging from 10^{13} to 3×10^{15} B/cm^2. The boron implantation doses were adjusted so that the implanted boron concentration at the depth of exfoliation would approximately correspond to the boron doping concentration of the epilayers. No thermal annealing was used to activate the implanted boron. During the implantation the wafer temperature was maintained below 100°C. After the implantation the implanted donor wafers were bonded to the Si or glass handle wafers using the plasma enhanced low temperature bonding process [4]. The bonded Si wafer pairs were annealed in a box furnace under N_2 in two steps: first for 2 hours at 100°C and then 2 hours at 180–450°C. After annealing some of the wafer pairs were cut with a dicing saw to rectangular slices. The energy required for the delamination of the implanted layer was measured by the crack opening method [5]. A blade was inserted between the bonded wafers and a crack propagating though the implanted region was created when the H-implanted layer was sufficiently weak compared to the bonded interface. The blade was inserted along the [110] direction for <100> and <111> Si wafers and along [111] for <110> Si wafers. The surface energy of the implanted layer was calculated based on the crack length measurement [5]. The surface roughness of the split layer was measured with Digital Instruments D3100 atomic force microscope (AFM) using silicon tips in the tapping mode. The lattice damage induced by the implantation was investigated by using 2 MeV $^4He^+$ Rutherford backscattering in the channeling mode and transmission electron microscopy (TEM). The thickness of the exfoliated layer was measured by conventional backscattering in the random mode. The electrical properties of the samples were investigated with a four-point probe, a hot probe and Hall-effect measurements.

RESULTS AND DISCUSSION

The basic condition for the mechanical exfoliation process is that the bonded interface is stronger than the hydrogen implanted layer (Fig. 1). The maximum

bond strength of oxide/Si bonds is achieved at 200–250°C if a proper plasma activation procedure is used [4]. When the implanted hydrogen dose is > 4 x 10^{16} H_2/cm^{-2} and the annealing temperature of > 250°C is used, the bonded interface is stronger than the hydrogen implanted region enabling mechanical layer transfer. The strength of the H-implanted layer drops down linearly with the increasing annealing temperature when a certain critical temperature is exceeded. This temperature, which is required for mechanical exfoliation, reduces with the increasing hydrogen dose. We have been able to transfer low doped Si layers after annealing at 200°C when a implantation dose of 5 x 10^{16} H_2/cm^2 was used.

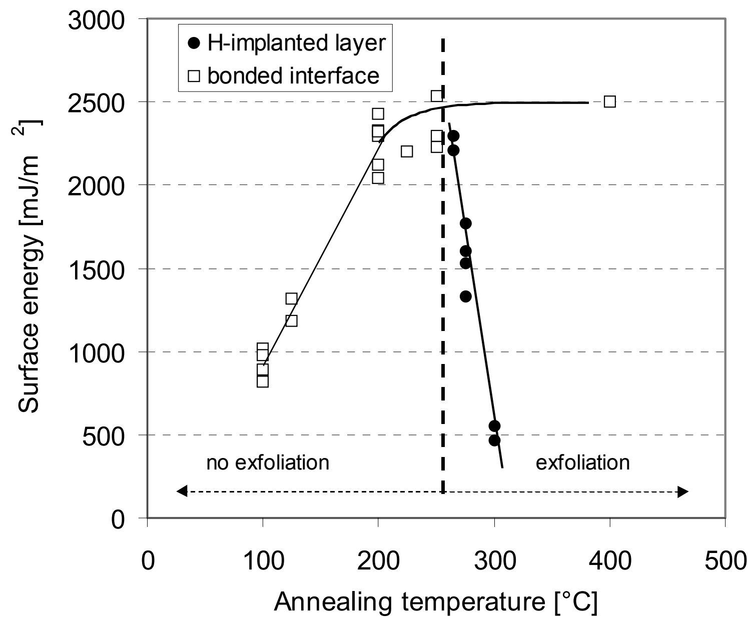

Fig. 1. Two-beam cross-sectional TEM-image (X30k) of the H-implanted and bonded <100> Si. The donor Si was implanted with H_2 at 100 keV with a dose of 5 x 10^{16} cm^{-2}. The implanted donor wafer was bonded to oxidized handle Si wafer using plasma assisted bonding process [4]. After implantation and bonding the sample was annealed at 250°C for 2 hours. The cut depth obtained by the RBS-measurement is marked on the figure.

Figure 2 shows cross-sectional TEM-image of the H-implanted and bonded <100> Si. The sample was annealed at 250°C after implantation and bonding. The damage zone caused by the hydrogen implantation can be observed as a

well-defined region having a thickness of ~200 nm. The Si areas outside the damage zone are essentially featureless. The RBS-measurement yielded a thickness of around 480 nm for the exfoliated layer. Comparison of TEM and RBS results suggests that the fracture takes place near the far end of the damage zone when the hydrogen dose of 10^{17} H^+/cm^2 is used.

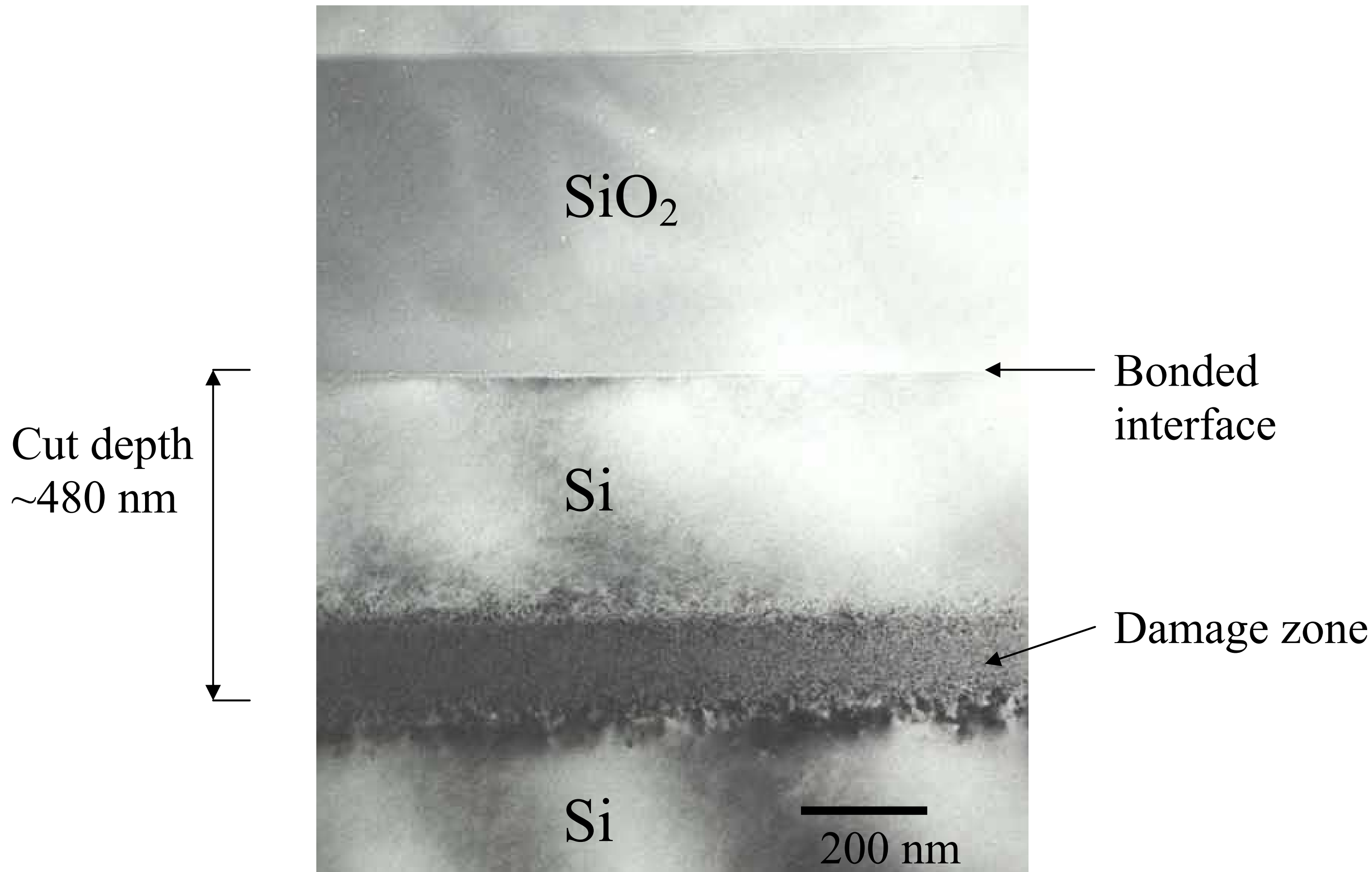

Fig. 2. Two-beam cross-sectional TEM-image (X30k) of the H-implanted and bonded <100> Si. The donor Si was implanted with H_2 at 100 keV with a dose of 5×10^{16} cm^{-2}. The implanted donor wafer was bonded to oxidized handle Si wafer using plasma assisted bonding process [4]. After implantation and bonding the sample was annealed at 250°C for 2 hours. The cut depth obtained by the RBS-measurement is marked on the figure.

The effect of boron doping and crystal orientation on the mechanical splitting of Si

The strength of the hydrogen implanted layer was found to decrease with increasing boron doping (Fig. 3) in agreement with the earlier results on surface blistering in H-implanted Si [6,7]. The samples implanted with boron prior to hydrogen implantation follow similar exfoliation behavior as the boron-doped epilayers. This indicates that the activation of the boron prior to H-implantation is not responsible for changes in the temperature required for mechanical splitting. The arsenic doped epilayers show no difference in the exfoliation behavior compared to undoped Si. If boron and arsenic are introduced simultaneously to obtain a heavily doped, compensated epilayer, the exfoliation strength is similar to that in the undoped Si. In B-implanted arsenic doped epilayers, the strength of the H-implanted layer is also similar to that obtained for undoped silicon. This spells out that the presence of the boron is not a sufficient condition for the lowering of the exfoliation temperature. It has been reported that crystal defects and shallow acceptors, such as boron, may trap hydrogen [8]. However, the damage due to boron implantation is not the primary reason for the reduced exfoliation strength, since our channeling RBS measurements showed that B+H co-implanted and B-doped H-implanted epilayers have less damage than the undoped samples implanted with hydrogen only. It has been reported that shallow acceptors in silicon are neutralized by monoatomic hydrogen [8]. This compensation effect involves silicon-hydrogen bonding. The boron neutralization and the associated Si-H bonding are suppressed by counterdoping with n-type impurities. Although this mechanism for hydrogen compensation of shallow p-type impurities provides mainly circumstantial similarities with our exfoliation experiments we propose that the same mechanism is responsible for the doping effects in the Si layer transfer. Measured by channeling RBS the lattice damage peak due to implantation appeared to move closer to the wafer surface if the peak concentration of boron is $> 10^{19}$ cm^{-3}. The depth of exfoliation was 478 nm for undoped Si and 460 nm for heavily boron doped samples. This shows that the exfoliation depth in Si is associated with the peak lattice damage generated by the implantation process.

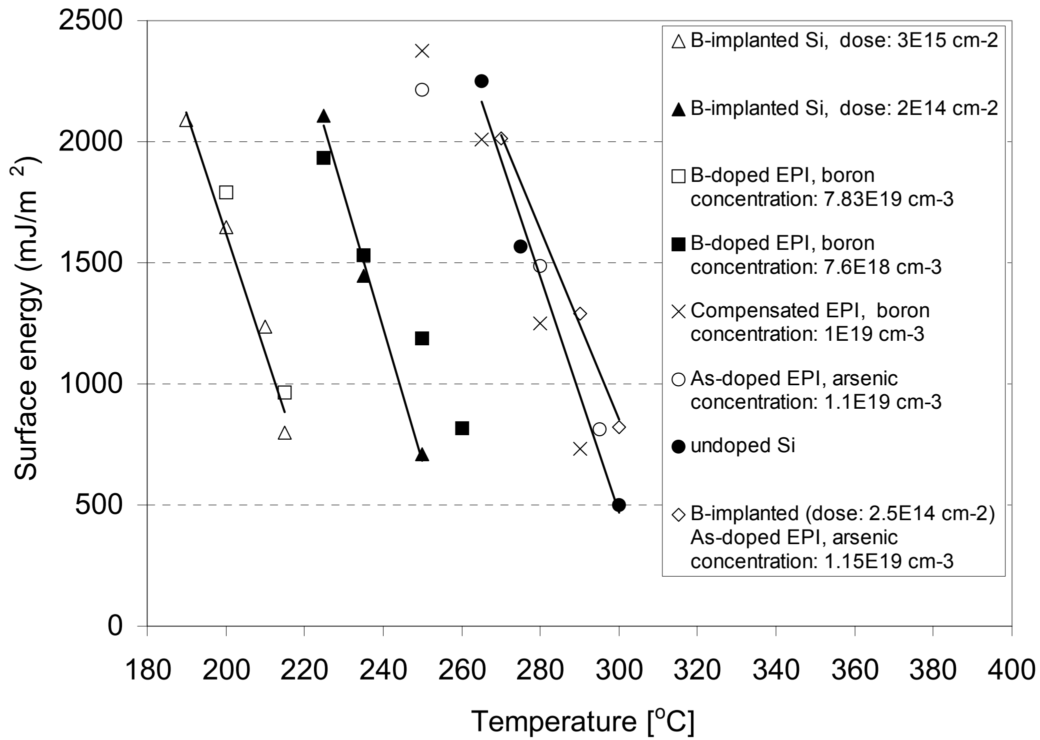

Fig. 3. The measured surface energy of the hydrogen implanted layer in <100> Si for the various doping schemes. The hydrogen implantation was done with H_2^+ *at 100 keV with a dose of 4.5 x* 10^{16} H_2/cm^{-2}*. The annealing time was 2 hours. The boron implantation doses were adjusted so that the implanted boron concentration at the depth of exfoliation corresponds approximately to the boron doping concentration of the epilayers.*

The strength of exfoliation was found to depend on the crystal orientation. The surface energies measured for the exfoliation process were 700, 1500 and 2300 mJ/m^2 for <100>, <111> and <110> oriented Si, respectively after annealing at 290°C. The thickness of the exfoliated layer was not affected by the crystal orientation being 478–488 nm for all samples. To understand the role of the implantation damage in producing the dependence on crystal orientation we studied separately the damage distributions in as-implanted samples. Using RBS channeling measurements we estimated that the normalized and corrected yield that can be attributed to scattering from displaced atoms is 5.5–7.5 % for all

three orientations. The result was obtained taking into account the differences in the intrinsic channeling yield along the different crystal axes and using appropriated normalization and correction methods [9]. Our result is similar to the data obtained by Zheng et al. [9] suggesting that the orientation has no significant effect on the disorder produced by the implantation.

Silicon on glass wafers formed by ion-cutting

Bonding of the donor Si wafer to a quartz glass (SOQ) or a Corning 1737F glass wafer (SOG) was carried out using plasma assisted bonding process without any intermediate layer between the wafers [4]. After plasma treatment the bonding occured spontaneously over the entire surface of the wafers under a slight applied pressure at the center of the wafers. No voids were detected at the bonded interface (Fig. 4). Since silicon and quartz glass have largely different thermal expansion coefficients we used H_2^+ + B^+ co-implantation to reduce the temperature needed for the exfoliation. The implantation doses were 3 x 10^{15} for B^+ and 4.5 x 10^{16} cm^{-2} for H_2^+. The Si/quartz wafer pairs were thermally split at 200°C because mechanical delamination process by the solid wedge was not found to be reproducible due to fragility of the glass wafers. However, it has been reported that more gentle peeling process can be obtained by a gas or liquid wedge [2,3]. Silicon on glass structure was formed using hydrogen implantation with a dose of 4.5 x 10^{16} H_2/cm^2. The splitting temperature was 400°C. The RBS channeling spectrum, <100> aligned, showed that the as-exfoliated Si layer on glass is crystalline in nature and the ion implantation damage is located near the surface of as-transferred Si layer. The AFM-measurement yielded an average surface roughness of 2.5–3.5 nm for the as-split surface of Si on glass layer (Fig. 5). As pointed out previously, the donor wafers used for SOG structures were B-doped CZ Si with a resistivity of 1–35 ohmcm. Using hot probe measurements, we found n-type conductivity in the implanted layer of the as-implanted wafers. The backside of the wafer remained p-type. The as-transferred Si layer and the as-split surface of the donor wafer were also found to be n-type after exfoliation at 400°C. The resistivity of the as-transferred SOG-layer was 0.1–0.3 ohmcm. At around 600°C the p-type conductivity of the exfoliated layer was restored. It is known that shallow donors are created in Si by hydrogenation. Some of these donors are associated with hydrogen enhanced thermal donors in CZ Si [10,11] and the others are caused by hydrogen and defect complexes [8]. We believe that the type of conversion

observed in our samples is due to the combined effect of ion-enhanced thermal donors and the precense of H-related shallow donors in the implanted layer.

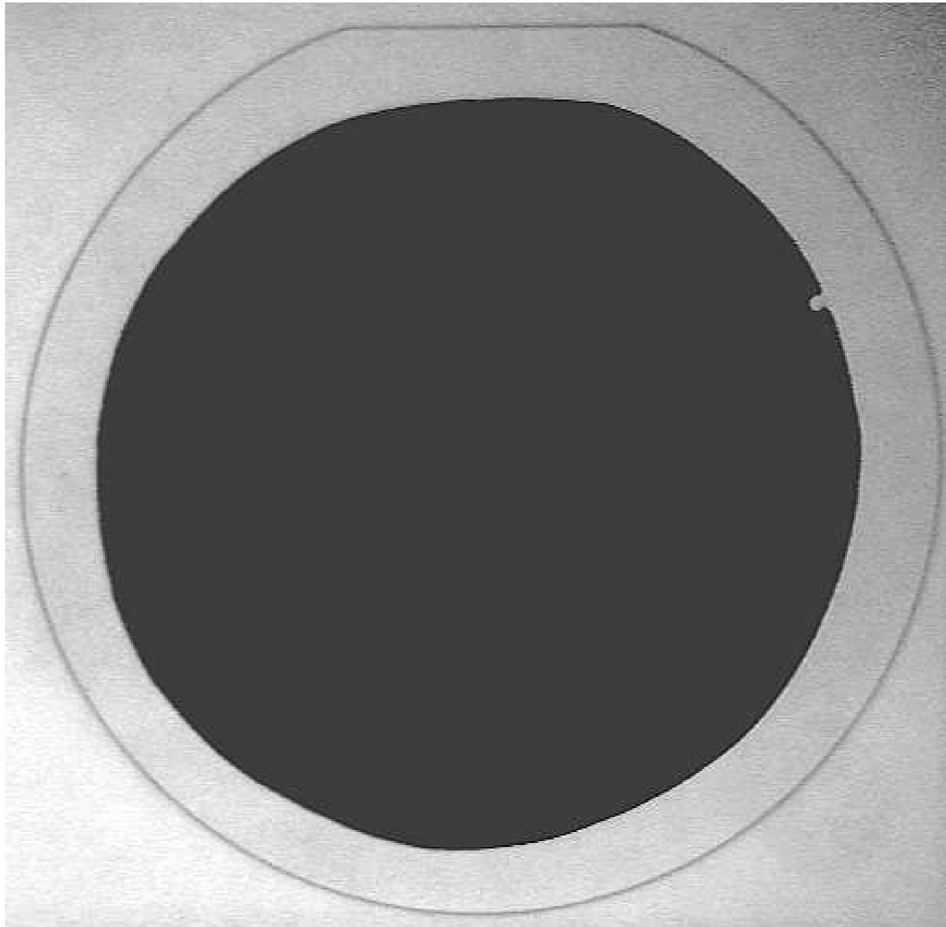

Fig. 4. The image of 100 mm silicon on quartz glass wafer. The wafer was exfoliated at 400°C. The dark area in the middle is the transferred Si layer with a thickness of about 480 nm. The outer white area is glass. No voids were detected at the bonded interface.

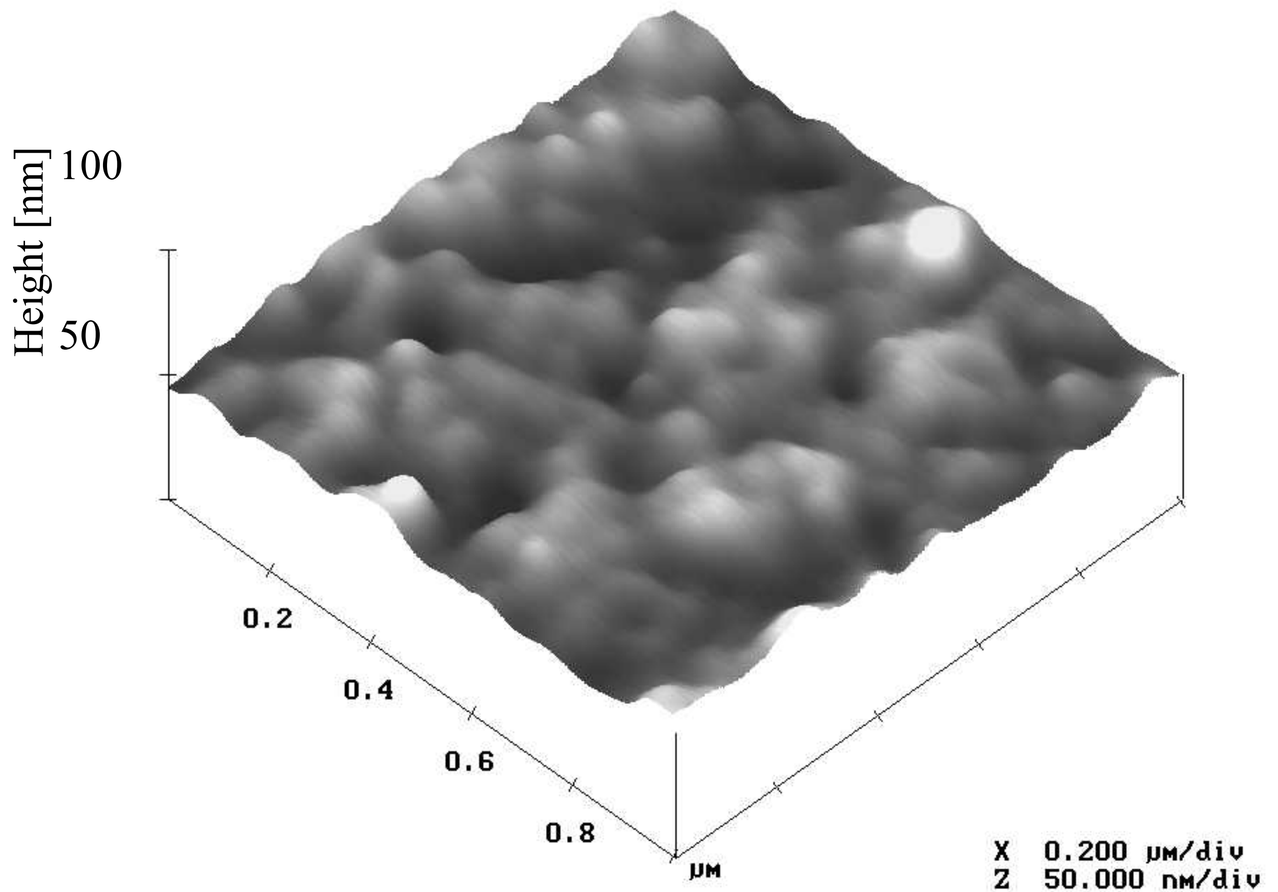

Fig. 5. AFM image of the as-split surface of silicon on glass layer. The average surface roughness (R_a) is 2.8 nm. The exfoliation was carried out at 400°C.

The p-type conductivity was restored at higher temperatures because of dissociation of the thermal donors and the out-diffusion of hydrogen. We direct attention to the fact that the restoration of the original conductivity type with reasonable carrier mobilities is a prerequisite for any useful application of these layers in electronics.

SUMMARY

We have found that, in silicon layer transfer process, the temperature required for exfoliation of silicon depends on the crystal orientation and boron doping. The cut depth is largely determined by the damage peak due to the implantation. The hydrogen implantation converted silicon wafer surface from p-type to n-type. The p-type conductivity was restored upon annealing at 600°C. Our results suggest that a good quality silicon on glass layer can be achieved by the ion-cutting process if the damaged surface region of the Si layer is removed.

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