Room-temperature bonding of epitaxial layer to carbon-cluster ion-implanted silicon wafers for CMOS image sensors

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We propose a fabrication process for silicon wafers by combining carbon-cluster ion implantation and room-temperature bonding for advanced CMOS image sensors. These carbon-cluster ions are made of carbon and hydrogen, which can passivate process-induced defects. We demonstrated that this combination process can be used to form an epitaxial layer on a carbon-cluster ion-implanted Czochralski (CZ)-grown silicon substrate with a high dose of $1 \times 10^{16}$ atoms/cm$^2$. This implantation condition transforms the top-surface region of the CZ-grown silicon substrate into a thin amorphous layer. Thus, an epitaxial layer cannot be grown on this implanted CZ-grown silicon substrate. However, this combination process can be used to form an epitaxial layer on the amorphous layer of this implanted CZ-grown silicon substrate surface. This bonding wafer has strong gettering capability in both the wafer-bonding region and the carbon-cluster ion-implanted projection range. Furthermore, this wafer inhibits oxygen out-diffusion to the epitaxial layer from the CZ-grown silicon substrate after device fabrication. Therefore, we believe that this bonding wafer is effective in decreasing the dark current and white-spot defect density for advanced CMOS image sensors.

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1. Introduction

CMOS image sensors have been widely used in mobile communication devices such as smartphones, tablets, and security sensors for monitoring and preventing collisions between automobiles.$^{1-3}$ Such devices require CMOS image sensors with high electrical performance.

However, contamination by impurities and remaining defects in the active region of electrical devices result in CMOS image sensor operation error. Figure 1 illustrates three serious technological issues with the CMOS image sensor fabrication process.$^{4-7}$ The first issue is metallic-impurity contamination during device fabrication.$^{5,6,8,9}$ The second issue is the out-diffusion of oxygen impurity to the epitaxial layer from the Czochralski (CZ)-grown silicon wafer substrate during device fabrication. The third issue is process-induced defects (PIDs) formed in the device-active region during device fabrication. The PIDs are generated in silicon crystal, for example, after ion implantation for the doping of n-type or p-type elements in silicon crystal, after deep etching for shallow trench isolation, and after ashing to remove photoresist in patterning photolithography.$^{7}$

Metallic impurities (for example, iron, copper, and nickel) contaminate the device-active region in CMOS image sensors during steps in the device fabrication such as dry etching, ashing, and rapid thermal annealing. These metallic impurities form deep energy levels in the space-charge region of photodiodes. These deep energy levels can act as generation–recombination centers that mostly affect electrical device parameters such as dark current and white-spot defect density.$^{10,11}$ Thus, they degrade the yield and reliability of CMOS image sensors.

The oxygen impurity out-diffuses to the device-active region in the epitaxial layer from the silicon substrate during heat treatment in CMOS device fabrication. This impurity also forms oxygen-related deep-level defects in the space-charge region of photodiodes.$^{12,13}$ These defects occur in the case of incomplete charge transfer due to the fixed-pattern noise generated during sensor charge transfer.$^{14}$ That is, these defects strongly affect electrical device performance such as image lag. Therefore, the possibility of forming an epitaxial layer on a silicon substrate at a lower temperature to inhibit out-diffusion from the CZ-grown silicon substrate to the epitaxial layer during epitaxial layer growth on the silicon substrate should be considered. However, the minimum temperature at which an epitaxial layer can be grown on a CZ-grown silicon wafer substrate is limited. We should also consider using a proximity gettering technique under the epitaxial layer to getter oxygen impurity diffusing to the device-active region from the CZ-grown silicon substrate during device fabrication. Thus, it is extremely important to study the effects of oxygen impurity on the electrical performance of CMOS image sensor devices as well as the metallic-impurity gettering techniques for CMOS image sensor fabrication.

There are several gettering techniques, and one of the most common is intrinsic gettering (IG), in which oxygen...
Fabrication flow of silicon wafer by combining carbon-cluster ion implantation and room-temperature bonding.

Fig. 2. Fabrication flow of silicon wafer by combining carbon-cluster ion implantation and room-temperature bonding.

precipitation is used to getter impurities in device fabrication. However, the fabrication temperature of advanced devices has been decreasing yearly. Consequently, it is extremely difficult to form a gettering sink by oxygen precipitation during device fabrication. Another approach to IG by oxygen precipitates is to perform heat treatment before device fabrication, which cannot form oxygen precipitates. With this approach, a pattern error occurs during photolithography due to the generation of oxygen precipitates. Furthermore, impurities contaminate the wafer during this heat treatment. Thus, it is necessary to change dummy wafers at every batch and clean the workspace components (for example, ports and stage) of equipment at fixed intervals.

Another commonly used gettering technique is ion implantation to easily control the gettering-sink volume. By this technique, it is necessary to implant ions on a wafer at higher doses to improve the gettering capability. However, if the epitaxial layer is grown on an ion-implanted wafer with a high dose, many defects are generated in the epitaxial layer as origin defects that remain on the ion-implanted wafer surface. To grow an epitaxial layer on an ion-implanted wafer surface, element ions are generally implanted on the silicon wafer with high energy to maintain the perfect crystallinity of the ion-implanted wafer surface. Because end of range defects (EORDs) are generated during ion implantation with high energy if the epitaxial layer is grown on an ion-implanted wafer with high energy, the defects will expand from the EORDs during heat treatment in device fabrication. These expanded defects will degrade the device yield and electrical characteristics of the device.

For high-sensitivity CMOS image sensors, it is necessary to decrease the effect of PIDs generated during device fabrication. Generally, a PID is passivated by light elements (hydrogen, nitrogen, oxygen, and fluorine) to become electrically inactive. This common method involves annealing in atmospheres of these light elements. However, because it is necessary to anneal at a temperature of over several hundred degrees for a long time by this method, impurities contaminate the silicon substrate and oxygen out-diffuses to the epitaxial layer from the silicon substrate.

Therefore, we propose a fabrication process for epitaxial-layer-bonding wafer as illustrated in Fig. 2. The ions were implanted into a base wafer at a high dose using a carbon-cluster ion implanter (Nissin Ion Equipment CLARIS). Carbon-cluster ions were formed by the ionization of a hydrocarbon compound by an electron-impact method. The species chosen for implantation were hydrocarbons, such as C3H5, because carbon can form a gettering sink in silicon crystals. In particular, oxygen precipitation is formed by carbon impurity in silicon crystals, and this precipitated oxygen can act as a gettering sink. Another reason is that hydrogen might passivate dangling bonds in the PIDs and metallic impurities in silicon crystals.

An epitaxial layer was grown on a bonding wafer, which was a CZ-grown silicon substrate. The bonding wafer with the epitaxial layer was then bonded to the base wafer with carbon-cluster ion implantation in ultra high vacuum at room temperature (EVG 580 ComBond/MWB-08-ST). Because it is not necessary to grow an epitaxial layer on a carbon-cluster ion-implanted wafer, it is possible to implant a silicon substrate with a high dose to generate an amorphous layer in the ion-implanted region, and it is not necessary to carry out
After implantation with a high dose, crystalline recovery annealing was performed.

After bonding the two wafers, the bonding wafer was ground and polished until an epitaxial layer formed on the back side, which is opposite the wafer-bonding region. In accordance with these steps, an epitaxial wafer was fabricated with carbon-cluster ion implantation at a high dose that could not be grown on an epitaxial layer. Regarding the epitaxial layer deposition on a silicon substrate with ion implantation, the generated defect density during the deposition of the epitaxial layer is in a trade-off relation with the ion implantation dose. Because our developed combination fabrication process does not require the growth of an epitaxial layer on a carbon-cluster ion-implanted wafer, it does not have any limitation regarding the dose or energy. Therefore, we believe that this process will be extremely important for fabricating epitaxial wafers.

### 2.1 Sample preparation

Table I lists the experimental conditions involving 200 mm wafers polished to 725 µm thickness. These wafers were made of (100) phosphorus-doped CZ-grown silicon single crystals. Their resistivity was 10 Ω cm and their oxygen concentration was 0.8 × 10$^{18}$ atoms/cm$^3$. As shown in Fig. 2, a substrate wafer as the base wafer was implanted from the surface with C$_3$H$_5$ carbon-cluster ions at 80 keV at a dose of 1 × 10$^{16}$ atoms/cm$^2$. Another wafer as the bonding wafer was grown on an epitaxial layer of 8 µm thickness using a Si$_3$HCl gas source at 1100 °C. These two wafers were bonded in ultrahigh vacuum under 1 × 10$^{-5}$ Pa at room temperature by connecting dangling bonds on the surface of the two wafers. These dangling bonds were formed on the top surface of the two wafers by irradiating argon ions at 1–2 keV to activate the surfaces. After bonding the two wafers, the bonding wafer was ground and polished until an epitaxial layer of 4 µm formed on the back side, which is opposite the wafer-bonding region. A reference sample was fabricated by growing an epitaxial layer of 4 µm on a silicon substrate without carbon-cluster ion implantation.

### 2.2 Experimental procedure

Figure 3 shows the experimental procedure. In step (a), we evaluated how many voids existed after bonding the epitaxial layer to the silicon substrate with carbon-cluster ion implantation using an infrared-transmission observation method to evaluate the quality of the epitaxial layer. In step (b), we evaluated the capability of gettering for oxygen and carbon by using secondary ion mass spectroscopy (SIMS) analysis and observing cross-sectional transmission electron microscopy (TEM) micrographs after heat treatment such as during device fabrication. In step (c), we evaluated the capability of gettering for hydrogen by using SIMS analysis after heat treatment such as during device fabrication. In step (d), we evaluated the capability of gettering for transition metals by using SIMS analysis after actual device fabrication.

### 2.2.1 Evaluation of voids after bonding epitaxial layer to carbon-cluster ion-implanted silicon substrate

We evaluated the voids after bonding the epitaxial layer to the silicon substrate, which was implanted with carbon-cluster ions, by using the infrared-transmission observation method with EVG301 equipment. This method detects voids using infrared radiation that transmits through the silicon wafer and is reflected at voids. The wavelength of this infrared radiation is above 1000 nm.

### 2.2.2 Evaluation of oxygen, carbon, hydrogen, and transition metal impurity gettering behavior

The oxygen, carbon, hydrogen, and transition metal impurity concentrations were measured through SIMS measurement using CAMECA IMS7f equipment. After heat treatment, small

![Fig. 3. Experimental flow. (a) Infrared observation, (b) evaluation of gettering for oxygen and carbon, (c) evaluation of gettering for hydrogen, and (d) evaluation of gettering for transition metal.](image)
high-dose implantation (dose: $1 \times 10^{16}$ atoms/cm$^2$) was at 5 Pa. The impurity concentration at about 4 µm under the wafer surface was estimated from the intensity of the impurity-related SIMS peaks in the SIMS spectra.

2.2.3 Evaluation of carbon-cluster ion-implantation-induced and wafer-bonding-induced defects. We used TEM to observe carbon-cluster ion-implantation-induced and wafer-bonding-induced defects. High-resolution TEM (HR-TEM) was used to characterize structural defects, such as carbon-cluster ion-implantation-induced and wafer-bonding-induced defects, before heat treatment (during bonding-wafer fabrication) and after heat treatment such as during device fabrication.

3. Results and discussion

3.1 Evaluation of voids formed during bonding of epitaxial layer to carbon-ion-implanted silicon substrate at room temperature under ultrahigh vacuum

Figure 4 illustrates the result of infrared-transmission observation for the 200 mm sample after bonding the epitaxial layer to the silicon substrate, which was implanted with high-dose carbon-cluster ions. Therefore, we conclude that this room-temperature-bonded wafer with high-dose carbon-cluster ion implantation is useful as an epitaxial wafer.

3.2 Oxygen- and carbon-impurity gettering behaviors after heat treatment

We evaluated the depth profile of the oxygen concentration by SIMS analysis of the samples involving bonding of the epitaxial layer to a silicon substrate implanted with carbon-cluster ions and an epitaxial wafer without carbon-cluster ions as a reference sample.

Figure 5(a) shows the depth profile of the oxygen concentration after wafer fabrication, and Fig. 5(b) illustrates that after heat treatment of 1100 °C for 2 h in nitrogen atmosphere, which are typical conditions during device fabrication. For the reference sample (epitaxial wafer), oxygen out-diffused to the epitaxial layer from the CZ-grown silicon substrate after wafer fabrication. However, for the room-temperature-bonding wafer, oxygen did not out-diffuse to the epitaxial layer from the CZ-grown silicon substrate after wafer fabrication. Furthermore, this room-temperature-bonding wafer contained a high concentration of oxygen (over $3.0 \times 10^{19}$ atoms/cm$^3$) between the epitaxial layer and silicon substrate. Oxygen knock-on occurred on the silicon substrate and epitaxial layer from the native oxide on the silicon wafer surface into the silicon wafer bulk when argon ions were irradiated to the silicon wafer surfaces to activate surface bonding for both the base wafer and the epitaxial layer of the bonding wafer.

For the epitaxial wafer, the oxygen concentration of the epitaxial layer surface increased by one order of magnitude from $3.5 \times 10^{10}$ to $4.0 \times 10^{12}$ atoms/cm$^2$ after heat treatment at 1100 °C for 2 h, which are typical conditions during device fabrication. However, for the room-temperature-bonding wafer, the oxygen concentration of the epitaxial layer surface increased from $3.0 \times 10^{16}$ to only $6.0 \times 10^{15}$ atoms/cm$^2$ after heat treatment. We assumed that because oxygen out-diffused to the epitaxial layer from the silicon substrate during heat treatment, the oxygen concentration increased after heat treatment. Additionally, we assumed that because oxygen was captured at the bonding and carbon-cluster ion-implanted regions, the oxygen concentration decreased near the bonding region (depth: ~1 to 0, 0 to 0.5 µm). Therefore, we conclude that this bonding wafer can inhibit out-diffusion from the CZ-grown silicon substrate to the epitaxial layer. This wafer can control the oxygen out-diffusion and the growth of oxygen.
precipitates to the epitaxial layer during heat treatment in device fabrication. We believe that device characteristics will further improve using this bonding wafer.

Figures 6(a) and 6(b) show expanded depth profiles of the oxygen and carbon concentrations obtained through SIMS analysis for the room-temperature-bonding wafer after wafer fabrication and the following heat treatment of 1100°C for 2 h in nitrogen atmosphere, respectively. As illustrated in Fig. 6(a), the oxygen concentration profile after wafer fabrication was symmetrical about the wafer-bonding region. Because oxygen is knocked-on from the native oxide on silicon wafers into the silicon wafer bulk, which is the silicon substrate and epitaxial layer, argon ions were irradiated on the silicon wafer surfaces to activate the bonding surfaces of both the bonding wafer and the epitaxial layer of the base wafer. Additionally, there was a high concentration of carbon contained in the silicon substrate after wafer fabrication. This profile was the same as that for the carbon-cluster ion-implanted sample in the experiment of Kurita and co-workers.29,30) During the fabrication of the room-temperature-bonding wafer, carbon was implanted into the silicon substrate, which is the base wafer. This implanted silicon substrate was then bonded to the epitaxial layer at room temperature without high-temperature heat treatment. Thus, because the room-temperature-bonding wafer did not have any heat treatment after carbon was implanted into the silicon substrate, this profile result is reasonable. As illustrated in Fig. 6(b), the oxygen concentration profile after heat treatment was not symmetrical about the wafer-bonding region. Oxygen out-diffused from the CZ-grown silicon substrate during heat treatment and was getters at the wafer-bonding and carbon-cluster ion-implanted regions.

Defects in this room-temperature-bonding wafer were observed near the wafer-bonding region through cross-sectional TEM. Figures 7(a) and 7(b) show cross-sectional TEM images of the room-temperature-bonding wafer after wafer fabrication and heat treatment (1100°C for 2 h), respectively. As shown in Fig. 7(a), there was an amorphous layer in the wafer-bonding region of the epitaxial layer and the carbon-cluster ion-implanted region of the CZ-grown silicon substrate. We consider that the amorphous layer in the epitaxial layer was formed by argon-ion irradiation for the surface activation of bonding and that the amorphous layer in the CZ-grown silicon substrate was formed by carbon-cluster ion implantation of the silicon substrate. As shown in Fig. 7(b), these amorphous layers recrystallized during heat treatment (1100°C for 2 h), and two types of defects remained in these amorphous layer regions. One type was misfit dislocations in the wafer-bonding region in the epitaxial layer and CZ-grown silicon substrate. The other type was dots in the carbon-cluster ion-implanted region in the CZ-grown silicon substrate. We call the dotted defects black-point defects. Therefore, we assume that these two types of defects remaining in the amorphous region will act as gettering sinks for oxygen out-diffusing to the epitaxial layer from the silicon substrate. A misfit dislocation generally acts as a gettering sink, and carbon can get oxygen.

As illustrated in Fig. 6(b), there was a high concentration of carbon in the wafer-bonding and carbon-cluster ion-implanted regions. Because this high carbon concentration was above the solid solubility in silicon crystal (3.3 × 10^{19} atoms/cm^3) after heat treatment, carbon existed not only in the substitutional sites but also in the interstitial sites and precipitated into this region in which the carbon concentration was above the solid solubility in silicon crystal. Because Kurita and co-workers argued that black-point defects in the carbon-cluster ion-implanted region are composed of carbon, we argue that the black-point defects in this room-temperature-bonding wafer are also mainly composed of carbon. Therefore, we assume that the oxygen getter in the wafer-bonding region results in misfit dislocations and that the carbon-cluster ion-implanted region contained black-point defects mainly composed of carbon.

### 3.3 Hydrogen-impurity gettering behavior after heat treatment

Figure 8(a) shows the depth profile of the hydrogen concentration obtained by using SIMS analysis for the room-temperature-bonding wafer (dose: 1 × 10^{16} atoms/cm^2) and the epitaxial wafer after wafer fabrication. For the epitaxial wafer, the hydrogen concentration was below the detection limit of SIMS analysis. However, for the room-temperature-bonding wafer, the hydrogen concentration was highest (over 1 × 10^{20} atoms/cm^3) between the epitaxial layer and silicon substrate. Because hydrogen is the lightest element, it easily out-diffuses in silicon crystal above 400°C. Thus, it is not possible for hydrogen to remain in the epitaxial wafer after its growth above 1000°C. We conclude that the
hydrogen concentration can be over $1.0 \times 10^{20}$ atoms/cm$^3$ in the epitaxial wafer in this fabrication process (carbon-cluster ion implantation to silicon substrate and room-temperature-bonded epitaxial layer).

Figure 8(b) shows the expanded depth profile of the room-temperature-bonding wafer after wafer fabrication (before heat treatment) and after heat treatment. The profile of the sample after fabrication corresponded to the hydrogen profile after carbon-cluster ion implantation to the silicon substrate. According to the profile of the sample after heat treatment, the hydrogen concentration decreased from $1.8 \times 10^{20}$ to $3.0 \times 10^{18}$ atoms/cm$^3$ and hydrogen out-diffused from the carbon-cluster ion-implanted region to the epitaxial layer. Thus, we believe that the hydrogen contained in the room-temperature-bonding wafer will passivate PIDs generated during device fabrication.

Hydrogen existed in the wafer-bonding and carbon-cluster ion-implanted regions after heat treatment. From the cross-sectional TEM image after heat treatment (Fig. 7), we assume that hydrogen is captured by misfit dislocations remaining in the wafer-bonding region and that the carbon-cluster ion-implanted region recrystallized to a silicon crystal. Misfit dislocations can generally capture hydrogen in implanted defects, similarly to a smart-cut silicon on insulator. Thus, we argue that misfit dislocations in the wafer-bonding region capture hydrogen. On the other hand, hydrogen existing as a monomer in silicon crystal out-diffuses from the silicon crystal above 400 °C. Thus, monomer hydrogen cannot exist in silicon crystal above 400 °C. However, in the room-temperature-bonding wafer, the hydrogen concentration remained at $3.0 \times 10^{18}$ atoms/cm$^3$ in the recrystallized silicon-crystal region after heat treatment above 400 °C. We conclude that the hydrogen in the carbon-cluster ion implantation region with recrystallized silicon crystal does not exist as a monomer. Therefore, we assume that this hydrogen in the carbon-cluster ion-implanted region with recrystallized silicon crystal is complex, and we will study this in the future.

### 3.4 Transition-metallic-impurity gettering behaviors after actual device fabrication

Figure 9 shows the depth profiles of the concentration per area on the room-temperature-bonding wafer after actual device fabrication obtained by integration. By integrating the concentration per volume in Fig. 9 to obtain the concentration per unit area, it was found that nickel, copper, and iron existed under the epitaxial layer with a concentration of over $1 \times 10^{14}$ atoms/cm$^2$ per unit area. We argue that this room-temperature-bonding wafer has gettering capability.

We fabricated another room-temperature-bonding wafer without carbon-cluster ion implantation, and actual devices were fabricated on this sample. The depth profile of iron for this wafer was then analyzed using SIMS. Figure 9(c) shows the SIMS analysis results of iron. The room-temperature-bonding wafer without carbon-cluster ion implantation captured iron only in the wafer-bonding region. In contrast, the room-temperature-bonding wafer with carbon-cluster ion implantation captured iron in the wafer-bonding and carbon-
cluster ion-implanted regions. Therefore, the room-temperature-bonding wafer with carbon-cluster ion implantation had two gettering sink components. One component was located in the wafer-bonding region and the other was located in the carbon-cluster ion-implanted region.

### 3.5 Gettering mechanism in wafer-bonding and carbon-cluster ion-implanted regions

There are generally two types of gettering sinks, relaxation and segregation types.\(^50,51\) For the relaxation type, because a gettering sink acts only below the supersaturated solid solubility, the gettered-metal-impurity concentration is below the solid solubility in silicon crystal. For the segregation type, because it is not always necessary that the atmosphere of a gettering sink is below the supersaturated solid solubility, the gettered-metal-impurity concentration is above the solid solubility in silicon crystal. Thus, a segregation type acts more stably than a relaxation type in silicon crystal regardless of the temperature.

Figure 10 illustrates the SIMS analysis results of the bonding wafer with carbon-cluster ion implantation after actual device fabrication including the solid solubility\(^8\) of metallic impurities (nickel, copper, and iron) in silicon crystal, as denoted by the dotted lines. The concentrations of these metallic impurities were above the solid solubility in silicon crystal after actual device fabrication. Thus, this bonding wafer had at least one segregation-type gettering sink. According to the cross-sectional TEM image [Fig. 7(a)] after wafer fabrication, amorphous layers were formed in the bonding and carbon-cluster ion-implanted regions. An amorphous layer generally acts as a gettering sink similarly to a polysilicon back seal.\(^52\) Thus, the amorphous layers in this bonding wafer will act as a segregation-type gettering sink. As shown in the cross-sectional TEM image [Fig. 7(b)] after heat treatment, such as during device fabrication, this bonding wafer had misfit dislocations in the wafer-bonding region and black-point defects in the carbon-cluster ion-implanted region.

When a silicon wafer has misfit dislocations, impurities are captured around these dislocations in the silicon crystal. In accordance with the Cottrell effect, the solid solubility of the impurity increases to relieve strains in the silicon crystal.\(^53,54\) This region near the dislocations acts as a segregation-type gettering sink.\(^53\) Yu and co-workers\(^55\) showed that copper segregated above the solid solubility in the wafer-bonding region after quenching heat treatment from 800 °C to room temperature. Aucouturier and co-workers\(^44\) showed that copper segregated into twins after heat treatment at 700 °C, and Maurice and Colliex\(^56\) showed that copper and iron segregated into grain boundaries after heat treatment at 900 °C. Our bonding wafer with carbon-cluster ion implantation bonded at room temperature had misfit dislocations in the wafer-bonding region after heat treatment, as illustrated in Fig. 7(b). This wafer segregated copper and iron to obtain concentrations above the solid solubility in the silicon crystal in the wafer-bonding region, as illustrated in Fig. 10. Pizzini and co-workers\(^57\) showed that oxygen and carbon segregated near grain boundaries. Our bonding wafer segregated oxygen and carbon in the wafer-bonding region, as shown in Fig. 6(b). Thus, our bonding wafer bonded at room temperature will have a segregation-type gettering sink in the wafer-bonding region.

The carbon-cluster ion-implanted region captured metallic impurities (nickel, copper, and iron), which had concentrations above the solid solubility in silicon crystal, as illustrated in Fig. 10. Implanted carbon generally acts as a gettering sink in silicon crystal.\(^17,19\) Wong and co-workers\(^17,18\) showed that copper and gold segregated in a carbon-ion-implanted region. Kurita and co-workers\(^29,30\) showed that the carbon-cluster ion-implanted region had black-point defects that were composed of interstitial carbon after fabricating an epitaxial wafer and that the interstitial carbon acted as a gettering sink. As illustrated in Fig. 6(b), because the carbon concentration was above the solid solubility in silicon crystal \((3.3 \times 10^{19} \text{atoms/cm}^3)\) in the implanted region, carbon was located at substitutional sites \((C_s)\) and interstitial sites \((C_i)\) in this implanted region. Shirasawa and co-workers\(^58-60\) indicated that the binding energy of metallic impurities at
4. Conclusions

We provided the first demonstration of the bonding characteristics and transition-metal-, oxygen-, and hydrogen-impurity gettering performance in the case of bonding an epitaxial layer to a C$_2$H$_5$-cluster ion-implanted silicon substrate. The epitaxial layer can be bonded to an amorphous layer of silicon substrate with high-dose carbon-cluster ion implantation at room temperature under high vacuum. Our bonding wafer has gettering sinks that are in the wafer-bonding and carbon-cluster ion-implanted regions for metallic, oxygen, and hydrogen impurities. This bonding wafer had a large amount of hydrogen (above 1.0 × 10^{20} \text{ atoms/cm}^2) after wafer fabrication. This hydrogen will passivate the PIDs formed during device fabrication. This wafer inhibits the out-diffusion of oxygen to the epitaxial layer from the silicon substrate during device fabrication. Thus, this wafer is expected to improve the electrical performance of CMOS image sensors, such as the electrical characteristic of image lag.

Therefore, we assume that this wafer is effective in decreasing the dark current and white-spot defect density in CMOS image sensors. Because this bonding wafer is fabricated using both room-temperature bonding and carbon-cluster ion-implantation techniques, the fabrication cost may be as high as that of a conventional epitaxial silicon wafer. However, the price of advanced CMOS image sensors may be set as high as that of conventional CMOS image sensors, allowing the wafer fabrication cost to be absorbed. Thus, we believe that such wafers will be beneficial for advanced and next-generation CMOS image sensor fabrication processes.

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