EBIC/PL investigations of dislocation network produced by silicon wafer direct bonding

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\begin{abstract}
Dislocation networks (DNs) formed by silicon wafer bonding were studied by means of Electron Beam Induced Current (EBIC) and Photoluminescence (PL). The measurements were performed on p–n junction diode structures prepared by ion implantation. EBIC signal was observed not only inside the diode structure, but also far outside the diode area. This finding demonstrates the ability of the bonding interface to efficiently collect minority carriers and indicates a high electrical conductivity of the dislocation network. In addition, circular inhomogeneities of charge collection were observed. The contrast of those regions was bright at high beam energies and turned dark or vanished at lower energies. The contrast behavior of the circular areas can be explained by local variations of collection efficiency and recombination at the DN, which might be a result of different density of oxide precipitates. PL mappings at 0.794 and 1.081 eV revealed similar circular areas.

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1. Introduction

Dislocations as active electrical components have been attracting the attention of the researchers for half a century [1]. However, controllable formation of the dislocations had been just a dream for a long time. It only recently became possible with the silicon wafer direct bonding technology.
The technology allows fabricating a regular dislocation network (DN) at the bonding interface [2], and gives full control over the dislocation density and morphology by tuning the twist and tilt angles between the two initial wafers. The present interest in DN is driven by their pronounced luminescence properties, originating mainly from the dislocation related luminescence [3] band D1-D4. The 1.5 μm emission wavelength of D1 renders DN potentially applicable as active components in silicon based light emitters for on-chip optical interconnects [4]. Another feature of DN is enhanced electrical conduction. Electron beam induced current (EBIC) investigation showed carrier transport over millimeter distance along DN [5]. Strongly enhanced electrical conductivity has been also observed in MOSFETs devices containing DN made on top of silicon on insulator (SOI) wafers [6]. Such behavior may be of substantial interest for novel electronic component [7].

In this work, EBIC and photoluminescence (PL) were performed to get inside detailed electrical, optical properties of DN.

2. Experimental details

The DN were formed by silicon wafer direct bonding technique. Wafers with the same type of doping were used, resulting in either n- or p-type substrates containing a DN plane parallel to the sample surface at a depth of several μm. The thickness of the top layer in n-type substrate samples was about 2 μm and about 3 μm in p-type substrate samples. Test p–n diodes were prepared by B⁺ ion implantation at 50 keV into n-type bonded wafers and P⁺ ion implantation at 135 keV into p-type wafers. In both cases the implantation dose was 1 × 10¹⁴ cm⁻². The implanted samples were subsequently furnace annealed at 1000 °C in N₂ atmosphere for 30 minutes, resulting in a junction depth of ~400 nm for both type of wafers. A SiO₂ layer with a thickness of 500 nm was deposited on the surface by Plasma Enhanced Chemical Vapor Deposition (PECVD) for insulation of the contacts. The metal contact was made by deposition of Al, and then the samples were annealed at 420 °C in H₂ atmosphere to improve the contact quality. A sketch of the sample structure is shown in Fig. 1.

EBIC measurements were performed by using the Al contact on the front side and the ohmic contact on the rear side of the substrate prepared by rubbing InGa alloy. The samples were measured at various beam energies, at room temperature.

Light Beam Induced Current (LBIC) and PL measurements were performed using an Argon ion laser working at λ = 514 nm or a semiconductor laser working at λ = 808 nm as excitation sources. The excitation beam was modulated and Lock-in detection of LBIC and PL signal was used. In case of PL, the luminescence was spectrally analyzed in a monochromator and detected by a liquid nitrogen cooled Ge detector. Micrographs of LBIC and PL were taken by scanning the focused excitation beam across the sample.

3. Results

Fig. 2 shows EBIC images recorded in an n-type substrate sample at beam energies of 30 and 15 keV. The p–n junction region is clearly seen between the two rectangles formed by the Al contacts. Surprisingly, EBIC signal was detected not only in the p–n junction area, but also far outside the p–n
Fig. 2. EBIC image of an n-type substrate sample recorded at 30 keV (left) and 15 keV (right). Rectangles labeled A, B and C, mark the positions where energy dependent collection efficiency measurements were performed (compare Fig. 5).

Fig. 3. Typical structure of the circular areas in an n-type sample at higher contrast settings (EBIC images taken at 30 keV).

Fig. 4. TEM images of dislocation networks: left — plane view, right — cross section view. The arrows mark some of the oxide precipitates at the bonding interface.

In the junction region, the EBIC current was found independent of the distance to the p–n junction region. Moreover, under certain imaging conditions, inhomogeneities in charge collection were detected. Namely, for penetration depths of the electron beam > 2 μm (energy > 17 keV), some circular bright regions were observed, the bright circular areas vanished or turned to dark (not show here) contrast in some cases for energies lower than 17 keV. At higher EBIC contrast settings, the circular features exhibit typically several circles of different current levels, as illustrated in Fig. 3. TEM observations revealed some oxide precipitates (OPs) along with the DNs at the bonding interface, as shown in the plane and cross section views in Fig. 4. The density of OPs was found to be approximately \(5 \times 10^8 \text{ cm}^{-2}\) at the circular regions and \(5 \times 10^{10} \text{ cm}^{-2}\) outside the circular regions.

In order to verify the excitation depth dependence and to exclude that the observed behavior is due to interface charging caused by the electron beam, LBIC measurements were performed on a fresh sample (not irradiated by the electron beam) at 514 nm and 808 nm excitation wavelengths. These wavelengths correspond to penetration depths in silicon of approximately 0.85 and 11.5 μm, respectively, and ensure similar measurement conditions as for EBIC at low (<17 keV) and high energies (>17 keV). In the first case, carrier generation occurs above the interface, and in the second case, both above and below the interface. The LBIC images obtained are similar to those of EBIC (compare Fig. 5) with the circular structures observed only for the excitation wavelength of 808 nm.
More information about the inhomogeneities in the network was obtained from energy dependent EBIC collection efficiencies \( \eta(E) \) measurements. Such measurements were performed at different positions marked in Fig. 2, at the p–n junction region (A), at the bright circular area (B) and at region outside the p–n junction with normal EBIC signal (C). The results are presented in Fig. 6. In the p–n junction region, the collection efficiency in the entire energy range is higher than at the other places. The bright circular area and the normal region (C) show similar behavior at low energies (7–15 keV), but strongly diverge for energies higher than 17 keV, with the collection efficiencies larger in the circular areas.

Circular bright areas were detected in p-type substrate samples, too. Charge collection efficiency in p-type substrate samples was, however, quite different from that of n-type substrate samples. The collection efficiencies in the whole sample are very low (\(~30\%\) in the p–n junction region and \(~22\%\) outside the p–n junction), and the contrast of the circular area is very weak (Fig. 7) in comparison with n-type substrate samples. \( \eta(E) \) shows an increase in the range from 5 to 7 keV, a decrease in the energy range from 7 to 18 keV, and then an increase again from 18 to 40 keV, as shown by the dashed line in Fig. 6.

PL measurements were carried out on an n-type substrate sample at 514 nm excitation wavelength. PL mapping revealed a reduced luminescence signal at both 0.794 eV and 1.081 eV in the circular areas (Fig. 8).

4. Discussion

The detection of EBIC signal over the whole sample area indicates substantial charge collection ability and the conductive properties of the DN. The charge collection is a result of an electrical barrier at the DN. Dislocation conduction has been reported for solar materials previously [9]. It was found that the dislocation conduction is responsible for the increased dark current of solar cells. However, the dislocations in solar cells usually contain electrically disconnected segments, making it difficult to
evaluate the conductivity of the dislocations \[10\]. It is expected that in an ordered array of dislocations (i.e. DN) the conduction effect of dislocations is more pronounced. Indeed, in n-channel MOSFETs containing an artificial DN, Ishikawa et al. \[6\] observed an enhanced electrical conductivity of more than 2 orders. Yu et al. observed electrical conduction of the DN in a p-type bonded wafer by cross section EBIC measurements \[5\], where the EBIC signal was detected along the bonding interface several millimeters away from the Schottky contact. The reason for the electrical conductivity of the DN is unclear, however. Kveder et al. \[10\] suggested that the electrical conduction of the dislocations can be attributed to the one dimensional dislocation band that might be partly-filled with carriers, showing a metallic-like conduction.

The transition of the EBIC contrast in the circular areas from bright at high energies (penetration depth > 2 µm) to dark at low energies (penetration depth < 2µm) clearly suggests that an electrical barrier exists at the bonding interface. This barrier collects minority carriers. Subsequently, they are transported to the p–n junction region, giving rise to EBIC signal over the whole sample area. The barrier is a consequence of the dislocation charge, which forms a cylindrical space-charge-region (SCR) around the dislocation line known as Read’s cylinder \[11\]. At the p–n junction region, it is suggested that there might be a kind of overlapping between the SCR of the p–n junction and that of the DN, leading to high EBIC signal. The smooth shape of the \(\eta(E)\) as well as the high collection efficiency in n-type substrate sample implies the overlapping, while the decrease of \(\eta(E)\) around 18 keV in p-type substrate sample as well as the overall low collection efficiency indicates an absence of overlapping of the SCRs. However, this argument should be further verified.

The LBIC measurements at 514 and 808 nm confirmed the existence of an electrical barrier at the bonding interface. The electrical inhomogeneity at the bonding interface is mainly caused by the intrinsic electrical properties of the DN (i.e. by electric charge of the OPs and the dislocations) as well as by the recombination properties.

Bright circular structures were also found by other group \[12\] in hybrid-orientation (110)/(100) direct silicon bonded wafers by EBIC. The structures seem to relate to HF etching of the intrinsic oxide layers prior to the wafer bonding, where small droplets of HF after the etching may hinder further
oxidation of the surface. Therefore these areas have a lower oxygen precipitate density after the wafer bonding process. This speculation can elucidate the different oxygen precipitate density in and outside the circular regions very well. However, no explanation is available so far for the different current levels inside the circles.

It is well known that fixed positive charges exist within the OPs in silicon [13], and the positively charged OPs induce accumulation around OPs in n-type silicon and depletion in p-type silicon. Such conditions will influence the recombination activity at the Si/OP interface, leading to enhanced recombination in p-type silicon [13]. Together with the charged dislocation lines, which are negatively charged in n-type and positively charged in p-type silicon, OPs will modify the electrical barrier along the dislocation lines. Fig. 9 gives the schematic view of positively charged OPs along the negatively charged dislocation lines in n-type silicon. Two regions, one of low and the other of high OP density are indicated. The barrier height correlates with the OP distribution. The mean barrier height in the region of high OP density is low, and in the region of low OP density it is high. The difference in the barrier height between both regions introduces a broad space charge region (SCR) in the region with low OP density and narrow SCR in the region with high OP density.

In n-type substrate samples, the changes of the EBIC contrast in the circular areas at low and high excitation energies can be understood in terms of both recombination and charge collection at the interface. At low beam energy (<17 keV), the generation of excess carriers takes place mainly above the DN. In the region with broad SCR (i.e. the region with low OP density) a slightly higher collection efficiency is expected because the carriers have to diffuse just a short distance to reach the SCR of the dislocation network, and this would result in a bright contrast in this region in general. However, in this region there may be an enhanced non-radiative recombination as well. Indeed, PL mapping at energies 0.794 and 1.081 eV clearly shows a decrease of the signal (see Fig. 8) in the circular regions, supporting the assumption of enhanced recombination (scattering of light at OPs has been proposed as another possible explanation [14] of the decreased PL intensity in the circular areas). The charge collection and recombination effects contribute, oppositely, to the formation of the contrast at low beam energy, so the contrast can be dark or missing.

At high beam energy (>17 keV), the generation volume reaches beyond the bonding interface. A considerable amount of carriers is generated near the bonding interface according to the depth-dose function of Everhart and Hoff [15]. Carriers generated in/near the SCR of the DN will be separated immediately by the electrical field and can be considered completely collected by the barrier. More carriers are collected in the region with broad SCR. Therefore the contrast appears bright in the region with low OP density. In case of p-type substrate samples, however, the dislocations as well as the OPs are positively charged [13]. Both induce a depletion layer around the DN. This will not cause a big difference on the barrier height in regions with high and low density of OPs. The bright contrast at high beam energy is likely caused by an enhanced recombination outside the circular region (with high density of OPs). Such enhanced recombination was reported [13] in p-type silicon containing OPs. High recombination rate in the region with high OP density is expected, because the Si/OP interfaces are rich on interface states.

Although some of the observations can be well explained in view of the recombination and charge collection properties of DN containing OP, some phenomena (e.g. mechanism of carrier transport along DN to p–n junction and the formation of a multiple circular areas on certain areas of the sample (Fig. 3)) are still unclear, and should be further investigated.
5. Summary

We studied electrical and optical properties of DN prepared by wafer bonding. Substantial electrical conduction of the DNs was observed. Circular inhomogeneities were found by EBIC and PL mapping. In n-type substrate samples, those circular inhomogeneities appear bright at high excitation energies (>17 keV), and their contrast turns to dark or vanishes at low excitation energies (<17 keV). The EBIC contrast behavior was attributed to local variation of recombination properties and collection efficiency, resulting from different OP densities along the DN. Inhomogeneities of the OP density distribution results in variations of the local barrier height in n-type substrate samples. Low OP density results in a higher barrier and a broader SCR, leading to higher charge collection in the regions with lower OP density. The PL maps indicate an enhanced nonradiative recombination at the circular areas with low OP density. Both opposite effects contribute to the formation of the EBIC signal. Although, many of the observations can be understood in terms of our explanation, some phenomena remain unexplained. More work should be done to clarify those properties of DNs.

References