Doctorial Thesis

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A Study on
Conformal Plasma Doping Process
with Self-regulating Characteristics
for Source/drain Extension

A Dissertation Submitted to the Department of
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1.1 Silicon device trend

In 1965, G. Moore observed an exponential growth of the number of transistors in a chip and predicted that this trend would continue [1.1-1]. Since large scale integrated circuits (LSI) was invented in the 1970s, it has made tremendous progress. LSI technology has provided us various advanced equipment (mobile PC, cell-phone, Internet, etc.). Metal-oxide-semiconductor field effect transistors (MOSFETs) are fundamental switching devices to perform logic operations in LSIs. Figure 1.1-1 shows the trends of increasing number of bits in a dynamic random access memory (DRAM) [1.1-2] and increasing number of transistors in a central processing unit (CPU) [1.1-3]. The Moore’s law says that density become double every 18 months [1.1-1], as indicated by the solid lines in Fig.1.1-1.

The trend of Moore’s law has been progressed by the downsizing of MOSFETs for the 40 years. The downsizing of MOSFETs has been based on the Dennard’s scaling rule [1.1-4], in which transistor size parameters not only horizontal dimensions such as channel length ($L$) and channel width ($W$) but also vertical dimensions such as oxide thickness ($T_{ox}$) and junction depth ($X_J$) were scaled by a factor of ($1/K$) as shown in Figure 1.1-2(a) and (b) [1.1-4] and Table 1.1-1 so that the gate delay decreased by a factor of $I/K$ at constant power density. In other words, such scaling provides high speed operation of circuits by a factor of $K$ without increase in power dissipation per chip area. Here, $I/K = 0.7$ in 2008 [1.1-5], for example. It is noted that decrease in $X_J$ and increase in doping concentration ($N_D$ for donor and $N_A$ for acceptor) are indispensable in the scaling trend.
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Figure 1.1-1: Trends of (a) number of bits in DRAM [1.1-2] and (b) number of transistors in CPU [1.1-3].

Table 1.1-1: Scaling of MOSFET by the scaling factor of $K$.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Before Scaling</th>
<th>After Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Length</td>
<td>$L$</td>
<td>$L/K$</td>
</tr>
<tr>
<td>Channel Width</td>
<td>$W$</td>
<td>$W/K$</td>
</tr>
<tr>
<td>Device Area</td>
<td>$A$</td>
<td>$A/K^2$</td>
</tr>
<tr>
<td>Gate Oxide Thickness</td>
<td>$T_{ox}$</td>
<td>$T_{ox}/K$</td>
</tr>
<tr>
<td>Gate Capacitance</td>
<td>$C_{ox}$</td>
<td>$C_{ox}/K$</td>
</tr>
<tr>
<td>Junction Depth</td>
<td>$X_j$</td>
<td>$X_j/K$</td>
</tr>
<tr>
<td>Power supply voltage</td>
<td>$V_{SS}$</td>
<td>$V_{SS}/K$</td>
</tr>
<tr>
<td>Threshold Voltage</td>
<td>$V_{T0}$</td>
<td>$V_{T0}/K$</td>
</tr>
<tr>
<td>Doping Concentration</td>
<td>$N_A$</td>
<td>$N_A*K$</td>
</tr>
<tr>
<td></td>
<td>$N_D$</td>
<td>$N_D*K$</td>
</tr>
</tbody>
</table>

Figure 1.1-2: Illustration of device scaling principles. (a): Conventional commercially available device structure in 1974. (b): Scaled-down device structure with $K = 5$. [1.1-4]
The future possibility of the downsizing of MOSFET was demonstrated experimentally on the p-MOSFETs with sub-10 nm gate length [1.1-6][1.1-7]. However, it was pointed out in 2004 that the performance improvement only by the scaling down of MOSFETs was questionable. For example, drain current per unit channel width should increase with downscaling according to the scaling theory. However, drain current per unit channel width presented in various conferences before 2004 for sub-100 nm gate length MOSFETs showed significant reduction as shown in Fig.1.1-3 [1.1-8].

In recent years, for generations after the 130 nm node (90 nm, 65 nm, 45 nm, 32 nm), new techniques of performance enhancers have been introduced to keep improvement of device performances. As a result, drain current per unit channel width has been continuously increased up to 32 nm node as shown in Fig. 1.1-4 [1.1-9][1.1-10]. The artificial channel strain to enhance carrier mobility by using e-SiGe and strained SiN has been introduced in the 90 nm and 65 nm nodes [1.1-11][1.1-12], and the high-k metal-gate (HiK-MG) technique also has been introduce in the 45 nm and 32 nm nodes [1.1-9][1.1-13]-[1.1-15]. The impact of these performance enhancers was very large as
shown in Fig. 1.1-5 [1.1-10]. Various techniques of process-induced strain are employed in today’s fabrications (e-SiGe, e-SiC, contact-etch-stop layer, stress-memorization technique, stressed gate metal, stressed contact metal, etc.) [1.1-9][1.1-11]-[1.1-19]. Future transistors, planar and non-planar, will also use these performance enhancers on both n-MOSFETs and p-MOSFETs.

![Figure 1.1-4: Performance improvement enabled by enhancers [1.1-10].](image1)

![Figure 1.1-5: Contribution of strain for enhancing drive current in modern transistor scaling [1.1-10].](image2)
In order to improve the device performance and maintain continuous improvement in short channel properties, new materials and new structures have been required in MOSFETs for 22 nm node and beyond, as shown in Figure 1.1-6 [1.1-20]. This trend demands multiple gates FET (MuGFETs) for 22-15 nm node, and gate-all-around (GAA) or nanowire devices in future because of their excellent short channel effect (SCE) control. However, there is a tradeoff between the electrostatic improvement of a GAA devices and the fabrication complexity for the gates surrounding a channel. Thus, some intermediate structures have been developed in an attempt to get better SCE controllability with the minimum process complexity [1.1-21]-[1.1-39], as shown in Figure 1.1-7. Fin field effect transistor (FinFET) is a combination of concepts of double-gate and vertical device, which provides a double gate device fabricated by relatively conventional device processes [1.1-29]. Tri-gate FET is different from the FinFET in the absence of a gate-blocking layer on the top. Trigate FETs have gates surrounding the three sides of the rectangular channel, which provides improved SCE controllability with reduced vertical topography requirements [1.1-30]. FinFETs and Tri-gate FETs have fin structure for source/drain extension, and the shapes of the extension are deferent from those of planar FETs. They have advantages of drain-induced barrier lowering (DIBL) and random dopant fluctuations (RDF) compared with planar FETs.
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Figure 1.1-6: Metal-oxide-semiconductor device and interconnect scaling roadmap [1.1-20].

Figure 1.1-7: Structures of FinFET, Tri-gate FET and GAA FET [1.1-10].
1.2 Requirements for source/drain extension doping

Figure 1.2-1 schematically illustrates the important issues of downsizing of MOSFETs in terms of SCE. Figure 1.2-1(a) shows a cross section of MOSFETs commonly used in LSIs, in which the source and drain are composed of deep source/drain regions and shallow extension regions. The punch through stopper regions, which are lightly doped with impurity of opposite polarity for the source/drain, are also formed. Formation of the channel is controlled by surface potential modulated by electrical field from the gate. From the viewpoint of electrical switch used in digital circuit, resistance between source and channel should be as low as possible to obtain large currents in on state, while it should be as high as possible to shut off leakage currents in off state.

When the gate length becomes short, in the off state, the source extension region is close to the space charge region around the drain extension region in which electrical potential is low due to the large drain bias, as shown in Fig. 1.2-1 (b). At the near drain region, the space charge region is rather suppressed by the electric field from the gate in the near surface region, but it extends far from the drain in the deep region due to electric field from the drain extension region, which is a two dimensional effect produced by the gate and the drain extension region. Since electric field in the drain space charge region assists drift of carrier from the channel to the drain strongly, subthreshold leakage current flows through the deep region even when the gate bias is zero in order to switch off the MOSFET. In order to reduce the subthreshold leakage current, shallow extension region is required because it suppresses the space charge intrusion in the deep region.

Figure 1.2-1(c) shows the schematic of the on state of the same MOSFET with the short gate length. In this case, series resistances located in the current path between the external source and drain terminals should be reduced. The channel resistance is reduced by shortening the channel length. It requires further reduction of lateral resistance (or sheet resistance) of the source/drain extension regions to obtain larger drain current by scaling down of MOSFETs.
Therefore, both shallow $X_j$ and low sheet resistance ($R_s$) of the source/drain extension regions are indispensable for further scaling down of MOSFETs. ITRS2010 update indicates the target of extension $X_j$ and $R_s$ for bulk MPU/ASIC (Extended Planar Bulk) as shown in Fig. 1.2-2(a) [1.2-1]. The $X_j$ shallower than 9 nm is needed for the 27 nm node and beyond. However, the sheet resistances required in ITRS2010 update for the $X_j$ of shallower than 9 nm are higher than those required in ITRS2002 update as shown in Fig. 1.2-2(b). The fact that the requirement has been compromised in the state of the art road map indicates the true difficulty in reducing $R_s$ for the shallow $X_j$. It means also that an ideal $R_s$ is lower than that required in ITRS2010 update. Therefore, reducing $R_s$ at shallow region ($X_j<10$ nm) was challenge for this study.

![Figure 1.2-1: Important issues concerned with source/drain extension in the scaling down of planar FET.](image)

- **(a)**: Schematic of planar MOSFET.
- **(b)**: Off state.
- **(c)**: On state of planar MOSFET with short gate length.
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Figure 1.2-2: Tradeoff between $X_j$ and $R_s$ for planar FETs required in ITRS. (a): For pMOS and nMOS in ITRS2010 update. (b): For pMOS in ITRS2002 update, ITRS2003 and ITRS2010 update.

For the MuGFETs, doping technique to form the extension regions on the sidewalls of fins is required for FinFETs, and furthermore, conformal doping technique is strongly required to form the extension regions uniformly on both top surfaces and sidewalls of fins for Tri-gate FETs. However, the conventional ion implantation (I/I) technique faces big challenges, because shadowing effects for sidewalls due to small spacing between the adjacent fins occur if a tilted ion beam is used to perform doping on the sidewalls [1.2-2].

The conformality is evaluated by the ratio of resistivity of fin sidewall to fin top surface, and the value close to unity means good conformality. In case of rotated ion implantation process using conventional I/I, the ratio of resistivity can be decreased to 2 for tilted angle of 45°. However, considering realistic 32 nm node design rules, tilted angle of ion beam is limited to 10° due to the shadowing from adjacent fins, and contribution of the sidewalls to the conduction path is limited under the condition [1.2-3]. Figure 1.2-3 shows the comparison of simulated drain current between Tri-gate FET with conformal source/drain extension junction and that with standard ion implant doping distribution [1.2-3]. It revealed that the performance of Tri-gate FETs with conformal doping was significantly improved due to the reduction of the $R_s$ of the sidewall junctions.
Another problem of the I/I process is amorphization of whole fin structures resulting in poor recrystallization during subsequent annealing [1.2-4]. Figure 1.2-4 shows cross sectional transmission electron microscope (TEM) images for thin-body Si fins, in which many defects and even poly-crystalline regions are found after recrystallization [1.2-4]. The whole fin can be easily amorphized when heavy n-type dopants such as As and P are implanted to form source and drain extensions [1.2-5], especially for narrow FinFETs [1.2-4]. This is a serious concern because it degrades the device performance and increases the variability [1.2-4]-[1.2-6]. This problem is not only for FinFETs but also for Tri-gate FETs.

Recently, *in-situ* doped epitaxial films were introduced to form uniform extensions on the fins [1.2-7]. Figure 1.2-5 (a) shows fins before epitaxial growth, and Fig. 1.2-5 (b) shows fins after the growth of the *in-situ* doped epitaxial films. It can be seen that the epitaxial films grew on the sidewalls. Figure 1.2-5 (c) shows the comparison of resistance between the conformal doping and the conventional I/I. The *in-situ* doped
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films enabled uniform junction formation, resulting in the 30% reduction of resistance. Following this paper, combination processes of conformal junction formation and/or in-situ boron doped SiGe epi for p-channel FinFETs and in-situ phosphorus doped Si epi for n-channel FinFETs were proposed [1.2-8]. For the n-channel FinFETs, the 20% resistance reduction and the 10% $I_{ON}$ increase compared to those fabricated by conventional I/I process were observed as shown in Fig. 1.2-6 (a). Also for the p-channel FinFETs, a 50% resistance reduction and a 25% $I_{ON}$ increase were observed as shown in Fig. 1.2-6 (b). These works indicate that FinFET performance benefits from the conformal doping techniques, in terms of reduction of parasitic resistance and control of SCE.

![Cross sectional TEM images showing amorphization, many defects and even poly-crystalline Si after recrystalization in thin-body Si](image)

*Figure 1.2-4: Cross sectional TEM images showing amorphization, many defects and even poly-crystalline Si after recrystalization in thin-body Si [1.2-4]*.
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Figure 1.2-5: Conformal doping technique for FinFET using in-situ doped epitaxial film growth on fin sidewalls. (a) Cross sectional TEM image of fins (12 nm in width with 40 nm in pitch) before the growth. (b) Cross sectional TEM image after the epitaxial growth. (c) Resistance reduction obtained by conformal doping as compared to conventional I/I [1.2-7].

Figure 1.2-6: $I_{ON}$ - $I_{OFF}$ characteristics of FinFETs. $I_{ON}$ is increased due to the resistance reduction achieved by conformal doping [1.2-8]. (a) n-channel FinFETs. (b) p-channel FinFETs.
1.3 Plasma doping for formation of extension regions

Plasma doping (PD) has been studied since the late 1980s by Panasonic [1.3-1][1.3-2] and University of Berkeley. Figure 1.3-1 shows a schematic of the PD system [1.3-2]. A Si wafer was directly immersed in plasma containing doping species. Figure 1.3-2 shows cross sectional scanning electron microscope (SEM) micrograph, in which a B doped layer in a sub-half micron trench was observed after the PD with process time of 30 min. The doped layer in a vertical sidewall was observed by a selective etching method. These pioneering works have indicated a possibility of PD for shallow junction formation and sidewall doping.

Applications of PD to form ultra shallow junction (USJ) were eagerly developed in the late 1990s [1.3-3][1.3-4]. Due to the direct immersion of wafers in the plasma containing doping species, ion transport issues under the condition of ultra low acceleration energy, which has been a significant problem of degradation of through put at low energy on conventional I/I technology, have been solved. Low energy ions are implanted into the Si substrate with high dose rate, and very shallow as-implanted impurity profiles are easily obtained compared with I/I. Table 1.3-1 shows $X_j$ in previous works using PD for pMOS before 2002. According to recent trend, $X_j$ is defined as the depth where dopant concentration is $5 \times 10^{18}$ cm$^{-3}$ in this thesis, but depth where dopant concentration is $1 \times 10^{18}$ cm$^{-3}$ is also sometimes used as $X_j$ in order to compare values of $X_j$ reported in other literatures. The latter definition is used in Table 1.3-1. The values of $X_j$ for pMOS were 50-65 nm before 2000, and $X_j$ of 27 nm was reported in 2000. However, $X_j$ of 10 nm for pMOS was not reported. Therefore, realizing the $X_j$ of 10 nm itself was a great challenge for this study in the beginning. Furthermore, low Rs in such USJ, as mentioned in Fig. 1.2-2, was another challenge. For nMOS, the $X_j$ of 25 nm was presented in 1999 [1.3-9], in which $X_j$ was defined at the As concentration of about $5 \times 10^{18}$ cm$^{-3}$.
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Figure 1.3-1: Schematic of PD system in year 1988 [1.3-2].

Figure 1.3-2: Cross sectional SEM micrograph showing B doped layer in a sub-half micron trench whose width is 0.45 µm and depth is 4 µm [1.3-2].
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Table 1.3-1: Junction depth in previous works using plasma doping for pMOS before 2002.

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Xj@1E18cm²</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>B. Mizuno et al.</td>
<td>60nm</td>
<td>B₂H₆ plasma, PMOS [1.3-5]</td>
</tr>
<tr>
<td>1997</td>
<td>M. Takase et al.</td>
<td>50nm</td>
<td>BF₃ plasma, B₂H₆/He plasma, PMOS [1.3-6]</td>
</tr>
<tr>
<td>1998</td>
<td>J. M. Ha et al.</td>
<td>65nm</td>
<td>BF₃ plasma, PMOS [1.3-7]</td>
</tr>
<tr>
<td>2000</td>
<td>D. Lenoble et al.</td>
<td>27nm</td>
<td>Plasma +RTA, PMOS [1.3-8]</td>
</tr>
</tbody>
</table>

As a part of this study, the sub-10 nm of Xj with low Rs for pMOS was demonstrated in 2004 as described in detail later [1.3-10]. In the same year, an improvement in the Rs/Xj trade-off due to the suppression of the anomalous boron diffusion by combination of BF₃ PD and spike annealing was reported as shown in Figure 1.3-3 [1.3-11]. After these, advanced CMOS transistors (65 nm node) were fabricated [1.3-11], and the improved dynamic performance of the devices fabricated by PD process was demonstrated [1.3-12]. These results suggest that PD process with standard spike annealing is suitable for the 45nm node devices. The advantage of PD on SOI CMOS performance was also confirmed [1.3-13]. Though Xj-Rs characteristic had to be pushed to shallower Xj and lower Rs region for scaled planar FETs beyond 45nm node, fatal issues concerned with manufacturability such as Rs uniformity, Rs repeatability and dosimetry came to be recognized [1.3-14]. It was generally considered that the origins of less Rs uniformity within a wafer and less Rs repeatability wafer by wafer were distribution and fluctuation of ion density in plasma. Demands for the Rs uniformity and the Rs repeatability for mass production are much stricter than the typical uniformity and repeatability of ion density in plasma. The origin of difficulty in dosimetry is considered that not only ions but also electrons come to a Si wafer surface in the case of PD. Therefore conventional Faraday cup is not suitable for measuring implanted ion current.

In order to realize conformal doping, several techniques have been proposed to overcome this problem including PD [1.2-3]. Conformality is expressed by the ratio of resistivity of sidewall to that of top surface, as described in section 1.2. For p-type doping, the value of 1.4 by PD was reported [1.2-3]. Figure 1.3-4 shows a scanning spreading
resistance microscopy (SSRM) image of fin structures doped with BF$_3$ PD [1.2-3]. The
doped layer in the sidewall was clearly observed. However, sputter erosion of fins was
pointed out for higher doses in PD [1.3-15]. For n-type doping, on the other hand, there
were few reports for conformal doping using PD in 2006 when this study was started.
Therefore, the fundamentals of PD for n-type doping were studied in this work. As a
result, difficulty in n-type doping on sidewall due to the low adsorption efficiency of
n-type dopants was revealed.

Thus, PD is eager to be developed to form shallow junction with low $R_s$ for
scaled planar FETs, sidewall junction for FinFETs, and conformal junction for Tri-gate
FETs. The problems to be solved for practical use in near future are $R_s$ uniformity, $R_s$
repeatability, dosimetry and n-type doping to sidewalls of fins.

Figure 1.3-3:  $R_s$ vs $X_j$ for PLAD and BF$_3$ ULE implantation. PLAD is the abbreviation of plasma
doping, and ULE is the abbreviation of ultra-low energy in [1.3-11].

Figure 1.3-4:  Scanning spreading resistance microscopy (SSRM) image of fin structure doped with BF$_3$
PD followed by spike-annealing at 1050°C [1.2-3].
1.4 Purposes, achievements and organization of this study

The purpose of this work is development of PD methods for practical use in CMOS LSI processes in near future. Significant problems to be solved for realizing such process technology have been discussed in this chapter. These are summarized as follows:

1. Development of processes to form shallow junctions with $X_j$ shallower than 10 nm and low $R_s$ satisfying the requirement for planar MOSFETs for 27-21 nm node.

2. Development of processes to form conformal junctions for FinFETs and Tri-gate FETs for 22 nm node and beyond.

For the above purposes, the following results are achieved in this study. The p-type and n-type junctions with $X_j$ of sub-10 nm were achieved after flash lump annealing by introducing newly developed He PD [1.3-10] technique or self-regulatory plasma doping (SRPD) [1.4-1, 1.4-3] technique. Shallow $X_j$ of 8.3 nm with low $R_s$ of 1448 ohm/sq was obtained for p-type junctions [1.4-1], which satisfied the requirement in ITRS2010 update for the MPU/ASIC Metal 1 (M1) ½ Pitch of 27nm; $X_j$ of 8.3 nm and $R_s$ of 1650 ohm/sq. For n-type junction, the very shallow $X_j$ of 7.2 nm, which was shallower than the ITRS requirement for the ½ Pitch of 22 nm (7.3 nm), with the low $R_s$ of 1286 ohm/sq was obtained [1.4-1]. The $R_s$ value was superior to the best value of I/I at the same $X_j$ reported so far.

The SRPD realized the shallow junctions and conformal junctions as described later. However, the mechanism of the SRPD process was not clear in the initial stage of this study. The essential physical parameters in SRPD were experimentally extracted, and a physical model to explain the phenomenon of $R_s$ saturation and the characteristics of conformal doping was established in this study.
Second, the manufacturing level of process controllability (<1-2% of 1 sigma on Rs uniformity, <1% on Rs repeatability, and <1% on dosimetry) has been realized for the first time in the PD process by utilizing the Rs saturation phenomena [1.4-2][1.4-3].

Conformal doping with the resistivity ratios (that of sidewall to top surface) of 0.85 for n-type doping [1.4-1] and 1 for p-type doping was achieved [1.4-3][1.4-4]. The conformal doping developed in this study contributed to enhance nMOS FinFETs performance, in which \( I_{\text{ON}} \) enhancement by 10% at same DIBL was achieved [1.4-5]. The demonstrated \( I_{\text{ON}} \) of 1.23 mA/\( \mu \)m for \( I_{\text{OFF}} = 100 \) nA/\( \mu \)m at 1 V was comparable to the state of the art FinFETs reported in literatures [1.4-6][1.2-8].

This thesis consists of five chapters as illustrated in Fig. 1.4-1. Following this Chapter 1, the PD systems used in this study, amorphization of Si in shallow region by He PD or SRPD, the influence of the amorphous layer to as-doped profiles, \( \chi_j-Rs \) property after annealing, and the characteristic of planar pMOSFETs are described in Chapter 2.

In Chapter 3, precise Rs repeatability by using conditioning plasma discharge technique, the Rs saturation phenomenon in the SRPD, and the precise dose controllability by using the Rs saturation phenomenon are discussed.

In Chapter 4, the mechanism of conformal doping using the SRPD is discussed.

Finally, in Chapter 5, the studies in this thesis are summarized and their future prospects are discussed.
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Figure 1.4-1: Contents of this thesis.
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Chapter 2

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Chapter 2. Ultra shallow junction formation

2.1 Introduction

USJs with low $Rs$ are required to control SCEs for scaled planar MOSFETs. However, this requirement is difficult to be satisfied by conventional I/I and rapid thermal annealing (RTA) for further scaling. Some new techniques have been proposed as the solutions of the requirement. Flash lump annealing (FLA) [2.1-1][2.1-2] and laser annealing (LA) [2.1-3]-[2.1-5] are ultra-short time and high temperature annealing methods. Almost no diffusion of implanted impurity during the annealing was achieved by these techniques, and USJs with $X_j$ shallower than 10 nm were achieved for doping by using conventional I/I or PD. However, reported $Rs$ values were not sufficiently low.

In this study, the new approach of PD utilizing He plasma was proposed to reduce $Rs$. Sub-10 nm of p-type junctions with low $Rs$ were demonstrated by He pre-amorphization PD (He PD) followed by B$_2$H$_6$ PD [1.4-1]. Furthermore, $X_j$ of 8.3 nm for p-type junctions and 7.2 nm for n-type junctions with low $Rs$ were achieved [1.4-2] by the SRPD, in which high He mass concentration and long bias time were used [1.4-4].

The first object of this chapter is to understand effects of the He PD on USJ formation process from the viewpoints of optical characteristics of Si surface, as-doped B profiles and $X_j$-$Rs$ property. Advantage of the B$_2$H$_6$ PD with preceding He PD on formation of USJs is demonstrated. The second object is to evaluate USJs formed by SRPD. The mechanism of SRPD is discussed from the viewpoint of similarity between He PD and SRPD. Application of SRPD to planar pMOSFETs is also discussed.

2.2 Plasma doping systems and experimental procedure

Three kinds of PD systems were used in this study. They are the system composed of a large process chamber equipped with inductively coupled plasma (ICP) source (referred to as PD system A), the system composed of a small process chamber equipped with ICP source (referred to as PD system B), and the system composed of a...
small process chamber equipped with Helicon wave plasma source (referred to as PD system C). Table 2.2-1 shows the summary of these PD systems.

<table>
<thead>
<tr>
<th>Item</th>
<th>PD system A</th>
<th>PD system B</th>
<th>PD system C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plasma source</td>
<td>Figure 2.2-1</td>
<td>Figure 2.2-2</td>
<td>Figure 2.2-3</td>
</tr>
<tr>
<td>2. Volume of the vacuum chamber</td>
<td>- ICP source</td>
<td>- ICP source</td>
<td>- Helicon wave source</td>
</tr>
<tr>
<td>3. Coils for generating plasma</td>
<td>- 93 L</td>
<td>- Almost 1/3 compared with PD system A</td>
<td>- Almost 1/3 compared with PD system A</td>
</tr>
<tr>
<td>4. Diameter of Si wafer</td>
<td>- Multiple coils</td>
<td>- Spiral multiple coils</td>
<td>- Coils are connected to the out side portion of the top window</td>
</tr>
<tr>
<td>5. Temperature of the Si wafer</td>
<td>- 300 mm</td>
<td>- 300 mm</td>
<td>- 200 mm</td>
</tr>
<tr>
<td>6. Gas supply tool</td>
<td>- Under 40°C during PD, Controllable</td>
<td>- Same as the system A</td>
<td>- Uncontrollable</td>
</tr>
<tr>
<td>7. Material gases</td>
<td>- Gas supply port at the center of the top plate</td>
<td>- Plural gas supply ports are set at the top plate</td>
<td>- Set at sidewall of vacuum chamber</td>
</tr>
<tr>
<td>8. Pressure in the vacuum chamber</td>
<td>- AsH₃/He mixture and He gas for n-type</td>
<td>- B₂H₆/He mixture and He gas for p-type</td>
<td>- B₂H₆/He mixture and He gas for p-type</td>
</tr>
<tr>
<td>9. Potential of the sample electrode</td>
<td>- B₂H₆/He mixture and He gas for p-type</td>
<td>- Controlled and kept constant during PD</td>
<td>- Controlled and kept constant during PD</td>
</tr>
<tr>
<td></td>
<td>- Controlled and kept constant during PD</td>
<td>- Negative. Controlled Vdc by RF power</td>
<td>- Negative. Controlled Vdc by RF power</td>
</tr>
</tbody>
</table>

Figure 2.2-1 shows the schematic cross-sectional view of the PD system A. Volume of the vacuum process chamber is 93 L. A 12-inch Si wafer is placed on the sample electrode in the chamber and the electrode is connected to an RF power supply. Temperature of the Si wafer is kept under 40 °C during PD process. A dielectric top plate is placed on the upper wall of the chamber and multiple coils are placed on the top plate and are connected to another RF power supply for plasma source. A gas supply port is located at the center of the top plate. An AsH₃/He mixture and He gases are supplied to the chamber through the mass flow controllers, which are used to control the total gas flow rate and the AsH₃ mass concentration in the chamber. The total gas flow rate is defined as the sum of the AsH₃/He mixture flow rate and the He flow rate. A vacuum exhaust port, in which a variable conductance valve to adjust working pressure in the chamber is equipped, is located at the bottom of the chamber. RF power is supplied to the coils so as to generate a magnetic field propagating into the chamber via the top plate.
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The magnetic field excites the AsH$_3$ diluted with He gas to plasma (i.e., the mixture of ions, radicals, neutral molecules, etc.). Electrical potential of the sample electrode is also controlled by the RF power supplied to the sample electrode. The potential is negative with respect to the plasma so that positive ions in the plasma are implanted into the Si wafer. The system has an inner chamber, not shown in the figure, for easy maintenance. The whole system has two process chambers for p-type and n-type doping. In case of p-type doping, B$_2$H$_6$ was used instead of AsH$_3$.

![Figure 2.2-1: Schematic of PD system A.](image)

Figure 2.2-1 shows the schematic cross sectional view of the PD system B. Volume of the chamber is almost three times smaller than that of the PD system A. Spiral multiple coils are placed on the top plate and are connected to an RF power supply for plasma source. Plural gas supply ports are located at the top plate. The system has one process chamber. Other components of the system are basically same as the PD system A.

Figure 2.2-3 shows the schematic cross sectional view of the PD system C. Helicon wave plasma source has the advantage of high ion density in plasma compared with ICP source. Volume of the chamber is almost three times smaller than that of the PD system A. A dielectric top window is placed on the upper wall of the chamber and
coils are placed outside of the top window and are connected to an RF power supply for plasma source. Gas supply ports are located at the sidewall of the chamber. An 8-inch Si wafer is loaded. Temperature of the Si wafer is room temperature at start of PD process, but it is elevated with process time due to the insufficient temperature control system. This is just because this system is for experimental uses. The temperature becomes typically 50 °C at the bias time of 20 s, and 100 °C at 60 s. The system has one chamber for p-type doping. Other components of the system are basically same as the PD system A.

![Figure 2.2-2: Schematic of PD system B.](image)

![Figure 2.2-3: Schematic of PD system C.](image)

After PD, the as-doped wafers were annealed by the RTA, FLA or all solid-state green laser annealing (ASLA). In the FLA, pre-heating temperature was varied.
between 700 and 725 °C, front side peak temperature was varied between 1275 and 1306 °C, and flash lamp irradiating time was 1 ms. In the ASLA, a green frequency-doubled diode pumped solid state laser (λ = 0.53 mm) irradiated the wafers for 100 ns with energy density between 1400 and 1500 mJ/cm².

Ion density in plasma was measured by Langmuir probe. The thickness and the optical parameters of the surface amorphous layers were evaluated by ellipsometry. The thickness of the amorphous layer was also measured by TEM. Rs was measured by four-point probe technique. B, As or He depth profiles after PD or after annealing were measured by low energy SIMS.

Figure 2.2-4 shows the as-doped B profiles in the same PD wafer measured by normal SIMS (sputtered from front side) and back-side SIMS. 250 eV O₂⁺ beam was used as a primary beam in this measurement. It was found that measured B concentration in near surface region was not reliable due to the knock on effect in the normal SIMS method. As far as this condition is used, B concentration of near surface shallower than approximately 2 nm is less reliable. On the other hand, profiles in the region deeper than approximately 3 nm is reliable. The surface peak was assumed to be correlated with B clustering or an artifact produced in the measurement [2.2-1].

![Figure 2.2-4: as-doped B profiles for the same PD wafer measured by normal SIMS and back-side SIMS.](image-url)
2.3  Pre-amorphization by He plasma (He PD)

Figure 2.3-1 shows the idea for formation of a B doped USJ with low $Rs$. Basic method is a combination of low energy B I/I followed by annealing such as FLA in which heating time is in order of millisecond as shown in (1) “B I/I + ms annealing” in the figure. Ge pre-amorphization implantation (PAI) technique is widely used for USJ formation process as shown in (2) in the figure, in which surface amorphous layer prevents implanted ions from channeling and its high optical absorption rate for the annealing light is expected to enhance activation of the implanted ions so as to obtain lower $Rs$. On the other hand, the $B_2H_6$ PD can provide very shallow as-doped B profile, however, it does not form the amorphous layer as shown in (3) in the figure. So, a possible good method is a combination of Ge PAI and $B_2H_6$ PD in which both very shallow as-doped profile and high optical absorption rate are utilized as shown in (4). However, this method needs two different doping process and different systems. If the pre-amorphization process is available in the same doping system of $B_2H_6$ PD, it is a better solution as shown in (5). Thus, development of such a pre-amorphization process is essential.

![Figure 2.3-1: Basis of the idea for forming B doped USJ with low Rs.](image)

Before B doping as-doped  After annealing  $X_j$  $Rs$

(1) B I/I  +ms anneal

(2) Ge PAI  +B I/I  +ms anneal

(3) $B_2H_6$ PD  +ms anneal

(4) Ge PAI  +$B_2H_6$ PD  +ms anneal

(5) PAI by PD  +$B_2H_6$ PD  +ms anneal

Figure 2.3-1:  Basis of the idea for forming B doped USJ with low $Rs$.
First, the results obtained using the PD system C were discussed. The plasma of B$_2$H$_6$ diluted by He was used. B$_2$H$_6$ mass concentration was varied between 5 mass% (He mass concentration of 95 mass%) and 0 mass% (He mass concentration of 100 mass%) [1.4-1]. PD using plasma of 100 mass%-He, i.e. no B$_2$H$_6$ contained, is referred as He PD in this thesis. In the following B$_2$H$_6$ PD, bias voltage, which is expressed by DC component, $V_{dc}$, induced by RF bias power in the PD system C, was varied from 30 V to 100 V, B dose after B$_2$H$_6$ PD was varied from 8x10$^{14}$ cm$^{-2}$ to 5x10$^{15}$ cm$^{-2}$, and bias time was varied from 7 to 60 s. In the He PD, $V_{dc}$ of bias was varied from 30 V to 310 V, bias time was 7 s, typical ion density in plasma was 5.5x10$^{10}$ cm$^{-3}$, and electron temperature was 6.5 eV. Source power was varied from 1000 W to 2250 W, working pressure was varied from 0.9 Pa to 2.5 Pa in both He PD and B$_2$H$_6$ PD.

Figure 2.3-2 shows the optical absorption coefficient of Si surface at wavelength of 460 nm after the B$_2$H$_6$ PD as a function of the B$_2$H$_6$ mass concentration. The $V_{dc}$ of bias was 100 V, source power was 1500 W, and pressure was 0.9 Pa. At the beginning, the data of B$_2$H$_6$ mass concentration of 5 and 0.025 mass% were obtained by B$_2$H$_6$ PD without He PD. It was found that the absorption coefficients of the surface layers were higher than that of c-Si and they were increased with the decrease of B$_2$H$_6$ mass concentration. And, it is noted that the absorption coefficient reached the level of typical a-Si at 0% in B$_2$H$_6$ mass concentration, that is, condition of He PD. Figure 2.3-3 (a) and (b) shows ion current density and electron temperature in the plasma. It is speculated that the large ion density and high electron temperature enhanced the amorphization of Si surface.
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Figure 2.3-2: Optical absorption coefficients of surface layers as a function of \(B_2H_6\) mass concentration. Absorption coefficients of a-Si and crystal Si are also shown by solid line and dotted line, respectively.

Figure 2.3-3: (a) ion current density and (b) electron temperature in the plasma as a function of \(B_2H_6\) mass concentration.

Figure 2.3-4 shows a cross-sectional TEM image after He PD. \(V_{dc}\) of bias was 60 V, source power was 1500 W, pressure was 0.9 Pa, and bias time was 7 s. An amorphous layer was formed in the near surface of Si substrate. Figure 2.3-5 shows the thickness of the amorphous layer as a function of \(V_{dc}\) of bias. Other process parameters besides the \(V_{dc}\) of bias were kept constant. The thickness was accurately controlled from 4 nm to 22 nm by changing the \(V_{dc}\) of bias from 30 V to 250 V. The linear relationship was maintained up to 22 nm, and it saturated over 250 V. (23.5 nm at 310 V was obtained.) From these results, it is considered that the amorphous layer is formed by high-flux He ion implantation. However, the plasma of He PD may contain B atoms due
to sputtering from the B deposited inner wall of the chamber though B$_2$H$_6$ was not supplied. Therefore, the contribution of B ions, which are ionized from the sputtered B atoms in the plasma, are another possible origin.

Figure 2.3-4: Cross-sectional TEM image of Si surface region after He PD under $V_{dc}$ of bias of 60 V.

Figure 2.3-5: Thickness of amorphous layer as a function of $V_{dc}$ of bias in He PD.

Figure 2.3-6 (a)-(d) shows the TEM images for the samples doped by He PD under $V_{dc}$ of bias from 75 V to 310 V. Source power was 1500 W, pressure was 0.9 Pa, bias time was 7 s. In case of the $V_{dc}$ of bias higher than 200 V, circular shaped bright regions whose diameter was smaller than 9.5 nm were clearly founded in the amorphous layer. From the TEM images, it is considered that the Si density in the bright region is lower than that in the dark region. It is known that similar circular regions are formed when a lot of He ions are implanted into Si by He I/I at doses over $1 \times 10^{16}$ cm$^{-2}$ [2.3-1] or $1 \times 10^{17}$ cm$^{-2}$ [2.3-2]. The circular shaped low Si density regions (referred to as the low
density regions) formed by He I/I are called bubbles or cavities in these literatures. It is also well known that the I/I of a lot of hydrogen ions in a Si wafer (the dose of 2x10^{16} -1x10^{17} \text{ cm}^{-2}) provides Si wafer splitting process for making SOI wafer in Smart-Cut process [2.3-3][2.3-4]. In He PD, a lot of He ions were doped in Si as referring as-doped He profile, as discussed in section 2.5. Although quantitative discussion comparing the He I/I in literature and the He PD is difficult since the acceleration energies are very different, 30-100 keV for the He I/I and lower than 300 eV for the He PD, the phenomenon is expected to be the same for both cases. The diameter of the low density regions became small by decreasing $V_{dc}$ of bias, and they were not founded in the case of 75 V. This is probably because the diameter became too small to be detected by TEM. From these results, it is considered that a lot of He ions implanted with low energy produced the amorphous layer during the He PD.

![Figure 2.3-6: Cross sectional TEM images for the samples treated by He PD. $V_{dc}$ of biases were (a) 75 V, (b) 150 V, (c) 200 V and (d) 310 V.](image)

Figure 2.3-7 shows the optical absorption coefficient of as-doped layers as a function of wave length, in which that of crystalline Si (c-Si) and intensity spectra of some typical light sources used in activation annealing are also shown. In the He PD, $V_{dc}$ of bias was 100 V, source power was 1500 W, and pressure was 0.9 Pa. The optical absorption coefficient after the He PD was as large as that after Ge PAI(5 kV, 1x10^{15} \text{ cm}^{-2}), and it was from 5 to 45 times larger than that of c-Si at the wavelength ranging from 400 to 800 nm. Such a large optical absorption in the shallow region is considered to be effective for high activation of impurities.
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2.4 Formation of B doped ultra shallow junctions by using He PD

2.4.1 Effects on as-doped profiles

Figure 2.4-1 shows as-doped B profiles after the B$_2$H$_6$ PD with and without preceding He PD. In He PD, source power was 1500 W, pressure was 0.9 Pa, bias time was 7 s, $V_{dc}$ of bias was 150 V. In the following B$_2$H$_6$ PD, B$_2$H$_6$ mass concentration was 5 mass %, source power was 1000 W, pressure was 2.5 Pa, bias time was 7 s, $V_{dc}$ of bias was 100V. Abruptness of the profile formed only by B$_2$H$_6$ PD was 3.2 nm/decade, while that formed by B$_2$H$_6$ PD with preceding He PD was improved to 1.7 nm/decade. In addition, these two profiles agree with each other in rather deep region where B concentration is lower than $1 \times 10^{18}$ cm$^{-3}$ and depth is deeper than 9 nm. This indicates that channeling of implanted ions is not affected by the pre-amorphization of He PD, and it is considered that channeling does not occur so significantly in the B$_2$H$_6$ PD originally. Thus, advantage of forming the amorphous layer by He PD is producing steep abruptness in high concentration region rather than suppression of channeling tail in low concentration region. This is different from the case of Ge PAI process used for I/I.
Figure 2.4-2 shows as-doped profiles similar to Fig. 2.4-1, in which a profile formed with higher $V_{dc}$ of bias (250 V) in He PD process is added. It is noted that the profile extended deeper for higher $V_{dc}$ of bias in He PD in spite of the condition of the subsequent B$_2$H$_6$ PD is the same. The higher bias voltage in He PD produces thicker amorphous layer as shown in Fig. 2.3-5. Thus, depth of B as-doped profile depends on the thickness of the surface amorphous layer. A possible origin of the phenomenon may be the Si low density regions as shown in Fig. 2.3-6. The distribution of the Si low density region extends deeper by using higher bias voltage. The range of implanted B ions is considered to be longer in the Si low density region due to less probability of collision between B and Si atoms, and most B ions enter deeper region easily to reach the buried normal density region through the low density region and they stop there efficiently.

Figure 2.4-3 shows the comparison of abruptness on as-doped profile between the B$_2$H$_6$ PD with preceding He PD and other reported results [2.1-2][2.4-1][2.4-2]. In this figure, as-doped depth is defined at the B concentration of $1 \times 10^{18}$ cm$^{-3}$. Very steep abruptness from 1.2 to 1.7 nm/decade at depth from 6 to 11 nm was obtained in this study, and they are obviously superior to the other reported ones.
2.4.2 Properties of formed junctions after activation annealing

Figure 2.4-4 shows $R_s$ and $X_j$ after the activation annealing as a function of $V_{dc}$ of bias of He PD. Process conditions for He PD and $B_2H_6$ PD were almost the same as those in previous experiments respectively except for $V_{dc}$ of bias in $B_2H_6$ PD was not 100 V but 200 V here. The activation annealing was performed by spike-RTA at 1000 °C. The dose of B and $X_j$ measured after the annealing were $2 \times 10^{15}$ cm$^{-2}$ and 28 nm in the all samples identically. It is considered that the $X_j$ was determined by B diffusion during the annealing and insensitive to the initial as-doped profile in this experiment due to relatively large thermal budget. On the other hand, $R_s$ was decreased by 30% by
introducing the He PD with $V_{dc}$ of bias of 150 V. The lower $Rs$ is considered to be
resulted from higher B concentration in the intermediate depth region (corresponding to
depth of 3-8 nm in Fig. 2.4-1) and larger optical absorption in the surface layer. However,
$Rs$ obtained for He PD with the high $V_{dc}$ of bias of 250 V was increased compared with
that of 150 V. This is probably because the low density regions became too large and
some crystalline defects were remained after the annealing. From these results, He PD is
a useful process to cope with both low $Rs$ and shallow $X_j$ when optimum bias voltage is
chosen.

![Figure 2.4-4: Rs and Xj depending on Vdc of bias of He PD.](image)

Advantages of He PD were evaluated also for the case of activation by ASLA.
Figures 2.4-5 shows SIMS profiles of B before and after ASLA for the B$_2$H$_6$ PD with
preceding He PD. Energy density of ASLA was 1500 mJ/cm$^2$. Diffusion length of B
during ASLA was only 2.5 nm, while the low $Rs$ of 588 ohm/sq was obtained. Figure
2.4-6 shows the variation of $X_j$ depending on the amorphous layer thickness formed by
He PD with various bias voltages for constant ASLA energy density (1500 mJ/cm$^2$). $X_j$
after ASLA became deep for thick amorphous layer. From this result, it is considered that
the light of ASLA is well adsorbed by the amorphous layer and B atoms diffuse rapidly
in the pre-amorphous layer. Thus, shallow $X_j$ was achieved by forming thin amorphous
layer with large optical absorption coefficient by He PD.
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Figure 2.4-5: B concentration profiles before and after ASLA.

Figure 2.4-6: Variation of junction depth depending on thickness of amorphous layer formed by He PD for constant ASLA energy density (1500 mJ/cm²).

Figure 2.4-7 shows the comparison of the abruptness of B profiles after annealing between this work and reported results [2.1-4][2.1-5][2.4-3]. The abruptness of 1.5 nm/decade at the $X_j$ of 10.5 nm was obtained. In the ITRS2010 update, the required values of extension lateral abruptness for bulk MPU/ASIC is 2.8 nm/decade at the $X_j$ of 10.5 nm at year 2011 [1.2-1]. The abruptness obtained in this work satisfied this requirement though $X_j$ is slightly deeper than the required value for the state of the art planar FETs. The steep abruptness after ASLA is due to the steep abruptness of as-doped profiles and the small diffusion length during ASLA.
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Figure 2.4-7: Comparison of the abruptness of B profiles after annealing between this work and reported results [2.1-4][2.1-5][2.4-3].

Figure 2.4-8 shows the $R_s$-$X_j$ plots for this work and other reported works using LA. The $X_j$ of this work was much shallower than the reported results obtained by I/I with Ge PAI and melt-LA [2.1-4][2.1-5]. The $R_s$ of this work was much lower than the reported results of submelt-LA[2.4-4]. These results indicate superiority of the B$_2$H$_6$ PD with preceding He PD on the $X_j$-$R_s$ property.

From these results, it was revealed that shallow, high concentration and steep as-doped B profile in the amorphous layer with large optical absorption coefficient was effective to reduce $R_s$ with keeping shallow $X_j$, and that the B$_2$H$_6$ PD with preceding He PD is a promising process to form shallow junctions with low $R_s$.

Figure 2.4-8: $X_j$ vs $R_s$ plots for this work and other reported works [2.1-4][2.1-5] [2.4-4] using LA.
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2.5 Formation of B doped ultra shallow junctions by SRPD

2.5.1 Properties of formed junctions

Besides the B$_2$H$_6$ PD with preceding He PD method, another method utilizing effects of plasma with high concentration He was developed in this study. This is named as SRPD. The former method is composed of two sequential processes of He PD and B$_2$H$_6$ PD. Contrast to it, SRPD is composed of single process. Significant property of SRPD is its good process controllability. However, it will be discussed precisely later in Chapter 3, including the origin of the naming of “self-regulatory”. In this chapter, SRPD is evaluated and discussed from the viewpoint of similarity with He PD.

Experiments of SRPD were carried out using the PD system A (see Fig. 2.2-1). In the B$_2$H$_6$ SRPD, Si wafers were doped with B using a B$_2$H$_6$ plasma diluted with He. This is the same as the previous B$_2$H$_6$ PD. The B$_2$H$_6$ PD and the B$_2$H$_6$ SRPD are distinguished by difference in He mass concentration and bias time. In the B$_2$H$_6$ SRPD, He mass concentration higher than 99 mass % (B$_2$H$_6$ mass concentration lower than 1 mass %) was typically used, and the doping time was so long, typically 60–200 s, that the $R_s$ after activation annealing was nearly saturated for doping time [1.2-4].

Figure 2.5-1 shows as-doped B profile after the B$_2$H$_6$ SRPD. B$_2$H$_6$ mass concentration was 0.73 mass %, source power was 500 W, pressure was 0.35 Pa, bias time was 60 s, peak-to-peak voltage ($V_{pp}$) of bias was 250V. Substrate bias is controlled by $V_{pp}$ in the PD system A, while it is controlled by $V_{dc}$ in the PD system C. The effect of the $V_{pp}$ of 250 V on the acceleration of implanted ions is equivalent to that of $V_{dc}$ of 125 V, a half of $V_{pp}$, approximately. B dose was 2.3x10$^{15}$ cm$^{-2}$, as-doped $X_j$ defined at the B concentration of 1x10$^{18}$ cm$^{-3}$ was 8.5 nm, and abruptness was 1.9 nm/decade. Although this abruptness was slightly degraded compared with that obtained by the B$_2$H$_6$ PD with preceding He PD (1.7 nm/decade) as shown in Fig. 2.4-1, it was still steeper than other reported results [2.1-2][2.4-1][2.4-2] as shown in Fig. 2.4-3.
Figure 2.5-1: $B$ concentration profile in as-doped state obtained by $B_2H_6$ SRPD.

Figure 2.5-2(a) shows a TEM image after the $B_2H_6$ SRPD. The well-defined amorphous layer is found in near surface region. This image is similar to Fig. 2.3-6(a) obtained using He PD with low bias voltage. No defects were remained after spike RTA as shown in Fig. 2.5-2(b). From these results, it is confirmed that an amorphous layer can be formed by the $B_2H_6$ SRPD.

Figure 2.5-3 shows as-doped He profile observed by SIMS after the $B_2H_6$ SRPD. The process condition was the same as the samples shown in Figs. 2.5-1 and 2.5-2(a). Since the detection limit of He concentration for the SIMS measurement was $1 \times 10^{19}$ cm$^{-3}$, the signal in region deeper than 30 nm seems to be noise. Thickness of the amorphous layer formed by the $B_2H_6$ SRPD was 8.7 nm including the native Si oxide of 1.8 nm as shown in Fig. 2.5-2, and He concentration at the amorphous/crystal interface (8.7 nm in depth) was found to be about $1 \times 10^{21}$ cm$^{-3}$ from Fig. 2.5-3. From these results, the mechanism of surface amorphization by the $B_2H_6$ SRPD is speculated that the total implanted dose of He with the long bias time increases He concentration in Si so as to exceed some threshold value (probably about $1 \times 10^{21}$ cm$^{-3}$) for amorphization.
Ion current density in B$_2$H$_6$ plasma diluted with He decreased 23 % by increasing B$_2$H$_6$ mass concentration from 0.005 mass% to 1.0 mass% in the PD system B. Unfortunately ion current density in the PD system A cannot be measured to avoid metal contamination from Langmuir probe, but it is reasonable that the trend of the decrease in ion current density with B$_2$H$_6$ mass concentration is similar between both PD systems because structures of both systems are similar each other except the chamber volume. Therefore, there is a possibility that ability of surface amorphization of the B$_2$H$_6$ SRPD becomes insufficient due to the low ion density compared with He PD. In fact, the
amorphization was insufficient when B$_2$H$_6$ mass concentration is large in the short bias time of 7 s for the PD system C as shown in Figs. 2.3-2 and 2.3-3. On the other hand, in case of B$_2$H$_6$ SRPD, the typical bias time is 8.6 times longer than that of He PD (60 s/7 s). Therefore, the total implanted dose of He was surely increased even if ion density was decrease by several ten % compared with He plasma.

Figure 2.5-4 shows SIMS profiles of a sample doped by the B$_2$H$_6$ SRPD before and after FLA. Extremely high concentration, over 7x10$^{21}$ cm$^{-3}$, peaks appear at the sample surfaces followed by plateau regions. In the plateau region, it can be assumed that almost all B atoms are activated. In contrast, the surface peak was assumed to be correlated with B clustering or an artifact produced in the SIMS measurement [2.2-1]. From these assumptions and Fig. 2.5-4, it is considered that carrier concentration is reached 3–7x 10$^{20}$ cm$^{-3}$. The diffusion length of B during FLA was only 1.2 nm. The shallow $X_j$ of 8.3 nm and the low $R_s$ of 1450 ohm/sq were obtained.

Figure 2.5-5 shows the $R_s$-$X_j$ plots for this work and other reported works using FLA. The $R_s$ of this work was much lower than the reported results by B I/I [2.4-5][2.4-6] in the region of $X_j$ shallower than 10 nm. In the ITRS2010 update, the requirement for drain extension of multi-gate MPU/ASIC (pMOS) is $R_s$ of 1650 ohm/sq at the $X_j$ of 8.7 nm at year 2013 [1.2-1]. Thus, the $R_s$ obtained in this study is suitable for the planar pMOSFETs. These results indicate superiority of the B$_2$H$_6$ SRPD on the $X_j$-$R_s$ property. In the millisecond annealing process era, as-doped profile will surely decide extension properties. From this viewpoint, the B$_2$H$_6$ SRPD is promising to achieve USJs with $X_j$ of shallower than 10 nm.
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Figure 2.5-4: B concentration profiles before and after FLA for B$_2$H$_6$ SRPD.

Figure 2.5-5: $X_j$ vs $R_s$ plots for this work and other reported works [2.4-5]/[2.4-6] using FLA.

Figure 2.5-6 shows the $R_s$-$X_j$ plots for this work and other reported works [2.1-2]/[2.4-7] using the B$_2$H$_6$ SRPD and spike RTA. The $R_s$-$X_j$ plots of this work exceeded the limit of $R_s$-$X_j$ plots obtained by various I/I. These results indicate superiority of the B$_2$H$_6$ SRPD on the $X_j$-$R_s$ property even when spike RTA is employed for annealing process.
Figure 2.5-6: $X_j$ vs $R_s$ plots for this work and other reported works [2.1-2][2.4-7] using spike RTA.

### 2.5.2 Application to pMOSFETs

Figure 2.5-7 shows process flow for planar pMOSFETs used in this study. Target physical $L_g$ was 80 nm. Two different plasma conditions of bias time in the $B_2H_6$ SRPD were employed. Bias time was varied at 60 and 200 s. $B_2H_6$ mass concentration was 0.73 mass%, source power was 500 W, pressure was 0.35 Pa, $V_{pp}$ of bias was 250V. The obtained doses and doping depths in as-doped state are summarized in Table 2.5-1.

Figure 2.5-8 shows the TEM images of planar pMOSFET fabricated using the condition of bias time of 60 s. Well re-crytallization is observed in the extension region. $V_{TSAT}$ rolloff characteristics of the devices using SRPD were better than those using I/I as shown in Fig. 2.5-9. This indicates that $X_j$ of SRPD is shallower than that of I/I after the activation. $I_{ON}$ for the $B_2H_6$ SRPD was improved by 14 % at the $I_{OFF}$ of $10^{-8}$ A/µm and by 26 % at $10^{-9}$ A/µm compared to that for I/I, as shown in Fig. 2.5-10. This is resulted from the shallow as-doped B profile with high B concentration and steep abruptness realized by the $B_2H_6$ SRPD. These advantages associated with the as-doped B profile produced extension regions with shallow $X_j$ and low $R_s$, and led the large $I_{ON}$. These results revealed the advantage of the $B_2H_6$ SRPD for the planar pMOSFETs of the $L_g$ of 80 nm.
Chapter 2. Ultra shallow junction formation

Figure 2.5-7: Process flow for planar pMOSFETs used in this study.

Table 2.5-1: Characteristics of as-doped state of SRPD obtained on bare Si wafers. The as-doped depth was defined as the depth at the B concentration of $5 \times 10^{18}$ cm$^{-3}$.

<table>
<thead>
<tr>
<th>Bias time (s)</th>
<th>as-doped B dosage (cm$^2$)</th>
<th>as-doped depth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>$2 \times 10^{15}$</td>
<td>6.7</td>
</tr>
<tr>
<td>200</td>
<td>$6.5 \times 10^{15}$</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Figure 2.5-8: TEM images of planar pMOSFET fabricated using $B_2H_6$ SRPD.
Chapter 2. Ultra shallow junction formation

Figure 2.5-9: Characteristics of $V_{TSAT}$-rolloff of the planar pMOSFETs fabricated using B$_2$H$_6$ SRPD or I/I (reference).

Figure 2.5-10: Characteristics of $I_{ON} - I_{OFF}$ of planar pMOSFETs fabricated using B$_2$H$_6$ SRPD or I/I (reference).
2.6 Conclusions

Properties of B doped USJs formed by PD have been improved to satisfy the requirements for future scaled pMOSFETs in this study. Original contribution for the achievement was proposal of He PD process and SRPD process, in which effects of plasma of pure or very high mass concentration He gas were utilized.

He PD produced well-defined amorphous layer with desirable optical absorption properties for activation annealing. The surface shallow amorphous layers were considered to be formed mainly by implantation of sufficient amount of low energy He ions. Most of implanted B ions entered the intermediate depth in the amorphous layer due to the Si low density regions preformed by He PD. This property produced shallow, high B concentration and steep as-doped B profiles for the B$_2$H$_6$ PD with preceding He PD, which was an advantage for USJs with low $Rs$ after activation annealing. Sub-10 nm USJs with low $Rs$ were achieved after laser annealing by using this new PD method.

Contrast to the two-step process of the above B$_2$H$_6$ PD with preceding He PD, B$_2$H$_6$ SRPD was a single step process, in which high He mass concentration, typically higher than 99 mass% and long bias time, typically 60–200 s were employed. USJ shallower than 10 nm ($X_j=8.3$ nm) was achieved after FLA by using the B$_2$H$_6$ SRPD. The $X_j$-$Rs$ property obtained by the B$_2$H$_6$ SRPD and FLA was suitable for the requirements of the maximum $Rs$ of drain extension regions for multi-gate MPU/ASIC (pMOS) at year 2013 in the ITRS2010 update. The $X_j$-$Rs$ property obtained by the B$_2$H$_6$ SRPD and spike RTA exceeded the limited region on $Rs$-$X_j$ plots obtained by various I/I and RTA so far. The origin of these good results was also the surface amorphous layer similar to the case of He PD. In SRPD, ion current density was decreased with mixing B$_2$H$_6$ gas, however, it was compensated by the long process time so as to form the surface amorphous layer. Therefore, the mechanism of formation of USJs with low $Rs$ is considered to be the same as in the case of the B$_2$H$_6$ PD with preceding He PD basically.

The $I_{ON}$ of planar pMOSFETs ($L_g=80$ nm) was improved by introducing the B$_2$H$_6$ SRPD by 14 % at the $I_{OFF}$ of $10^{-8}$ A/µm and by 26 % at that of $10^{-9}$ A/µm compared
to that by using I/I. These results of $X_{j-Rs}$ property and planar pMOSFET’s ($L_g= 80 \text{ nm}$) performance indicate a possibility of PD to enhance scaled planar pMOSFETs performances.
References


[2.4-6] T. Onizawa, S. Kato, T. Aoyama, K. Ikeda, and Y. Ohji, “The fabrication of low leakage junction with ultra shallow profile by the combination annealing of 10-ms low power and 2-ms high power...

Chapter 3
Process control

3.1 Introduction

3.2 Process control by utilizing Rs saturation phenomenon

3.2.1 Rs saturation phenomenon in SRPD

3.2.2 Within-wafer Rs uniformity

3.2.3 Effects of B₂H₆ mass concentration

3.2.4 Effects of deposition or sputtering

3.3 Improvement of Rs repeatability by conditioning plasma discharge method

3.4 Conclusions
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3.1 Introduction

Plasma doping (PD) has been proposed as one of the candidates to form USJs or conformal junctions for scaled devices. PD has several advantages such as shallowness, steep abruptness, lower $Rs$ and conformality of resistivity. However, there have been several concerns on PD as a production method in terms of dose uniformity, dose repeatability and dose controllability [1.3-13].

The object of this chapter is to overcome these problems for PD used in productions. The problems of less dose uniformity and less dose controllability were well improved by utilizing the peculiar $Rs$ saturation phenomenon. The problem of less dose repeatability was overcome by the conditioning plasma discharge method. Mechanisms of the $Rs$ saturation phenomenon and the conditioning plasma discharge method are also studied in this chapter.

3.2 Process control by utilizing $Rs$ saturation phenomenon

3.2.1 $Rs$ saturation phenomenon in SRPD

In SRPD process, it was found that doping time dependence on dose and $Rs$ after activation annealing exhibited saturation characteristics, as discussed in this chapter. This property is of benefit to process controllability greatly.

The experimental procedure and conditions employed here are as follows. 300 mm n-type Si wafers were doped with B by B$_2$H$_6$ SRPD in the PD system A. Pressure was 0.35 Pa, source power was 500 W, $V_{pp}$ of bias was 250 V, B$_2$H$_6$ mass concentration was 0.73 mass%, total gas flow rate was 30 cm$^3$/minute. The bias time was varied in wide range up to 800 s in this experiment. After B$_2$H$_6$ SRPD, the wafers were annealed at 1075 °C for 20 s. The high temperature of 1075 °C and the long annealing time of 20 s resulted in the high activation rate of B so that dose and its uniformity were precisely evaluated by $Rs$ measurement. The values of $Rs$ were measured after the annealing at 121
points on a 300 mm wafer using a four-point probe method with 3 mm wafer edge exclusion. Average of the Rs in the wafer was calculated from these 121 values of the Rs. Within-wafer Rs uniformity was defined as the standard deviation (1 sigma) of these 121 values of the Rs. Wafer to wafer Rs repeatability was defined as the standard deviation (1 sigma) of the values of the averaged Rs in a wafer obtained from plural wafers. For some conditions of B\textsubscript{2}H\textsubscript{6} SRPD, two wafers were doped using the same condition, and the Rs distribution was evaluated on one wafer and SIMS measurement of B concentration profile was carried out on the other wafer. Based on the calibration, B doses for all conditions of B\textsubscript{2}H\textsubscript{6} SRPD were evaluated from the Rs in a wafer.

Figure 3.2-1 shows the average of Rs in a wafer as a function of bias time, and Figs 3.2-2(a), (b) and (c) show expanded views of Fig. 3.2-1 for the bias time ranges of initial, middle and long. The Rs decreased rapidly for the bias time in the initial time range, shorter than 40 s. The rate of decrease in Rs slowed down in the middle time range, 45–200 s, and finally it reached the lowest and time-independent constant rate in the long time range, longer than 200 s. Fig. 3.2-3 shows B dose measured by SIMS as a function of bias time in the middle time range. In this time range, B dose increased linearly with bias time (Dose = a \times Time +b). Fig. 3.2-4(a) shows as-doped B profiles after B\textsubscript{2}H\textsubscript{6} SRPD for various bias times, and Fig. 3.2-4(b) shows an expanded view of Fig. 3.2-4(a) for the region near the surface. The black, green and red lines indicate the bias times of 60, 120 and 200 s. B concentrations in the region near the surface were clearly increased with bias time as referring B concentrations at the depth of 3 nm, and they were larger than 8x10\textsuperscript{20} cm\textsuperscript{-3}. These B concentrations are larger than the expected carrier concentration after FLA as discussed relating with Fig. 2.5-4. As-doped depth was increased with the bias time. This is due to increase in the thickness of amorphous layer for the long bias time [3.2-1].
Figure 3.2-1:  Average of Rs in wafer as a function of bias time.

Figure 3.2-2:  Expanded views of Fig. 3.2-1 for the bias time ranges of (a) initial, (b) middle and (c) long.

Figure 3.2-3:  B dose evaluated by SIMS as a function of bias time.
Figure 3.2-5 shows relationship between B dose measured by SIMS and $R_s$. It seems that exponential increase in B dose is needed for the reducing $R_s$ in the high B dose region. This is because the activation rate of B should be decreased for such high B dose. From this consideration, a conversion equation from $R_s$ to as-doped B dose was derived from fitting to the experimental data as shown in Fig. 3.2-5 using least squares method as follows;

$$D = 2.74 \times 10^{17} \times \exp (-0.0193 \times R_s)$$

(1)

where $D$ denotes the as-doped B dose, $R_s$ denotes sheet resistance after annealing at 1075 °C for 20 s.

Figure 3.2-6 shows B dose evaluated from $R_s$ by using Eq. (1) as a function of bias time, and Fig. 3.2-7 shows an expanded view of Fig. 3.2-6 for the middle time range with linear scale of vertical axis, which is the same as Fig. 3.2-3 substantially. The B dose increased rapidly with the bias time in the initial time range. However, the increase in B dose slowed down and the dose rate became constant in the middle time range, which is suitable for precise control of B dose by the bias time.

It is considered that B ion implantation into Si, B radical adsorption on Si
surface and B sputtering from Si surface take place simultaneously during B_2H_6 SRPD. In the initial stage, B concentration near the Si surface is not so high that increase in dose by ion implantation and radical absorption dominates without apparent dose loss by sputtering. In the middle time range, on the other hand, dose loss by sputtering becomes significant and the dose rate is defined by a balance of ion implantation, radical absorption and sputtering. In the long time range, the situation is similar, but another effect of B deposition discussed later in section 3.4 is added.

Figure 3.2-5: Relationship between B dose measured by SIMS and Rs.

Figure 3.2-6: B dose as a function of bias time.
3.2.2 Within-wafer $R_s$ uniformity

Figure 3.2-8 shows within-wafer $R_s$ uniformity as a function of bias time. $R_s$ uniformity was from 2 to 8 % (1 sigma) in the initial time range, but it was improved to be lower than 2 % in the middle time range. Fig. 3.2-9 shows typical distribution maps of $R_s$ obtained for the bias times of (a) 60 s and (b) 120 s, and their uniformity was 1.0 % and 0.73 %, respectively. The $R_s$ distribution of rotation symmetry was seen for the bias time of 60 s but it disappeared for the bias time of 120 s. The distribution pattern for the 60 s is probably due to an effect of distribution of ion density in the plasma.
The mechanism of improving $R_s$ uniformity is discussed here. The experimental condition employed here was close to but a slight different from that used for Figs. 3.2-1 and 3.2-8. Thus, a new data set is used in this discussion. Figure 3.2-10 shows the distributions of $R_s$ in Si wafers for the bias times from 20 to 200 s. Figs. 3.2-11(a) and (b) show the average of $R_s$ and $R_s$ uniformity as a function of bias time, in which the $R_s$ saturation trend is also found. Referring the result of the bias time of 20 s, $R_s$ at the center of Si wafer was lower than that in the wafer periphery region as shown in Fig. 3.2-10. This is probably due to large ion density at the center of plasma, which provide higher B dose at the center of the Si wafer. On the other hand, higher surface B concentration at the center of wafer leads larger dose loss by sputtering. Therefore, dose rate at the center of wafer slows down earlier in the progress of doping process. As a result, dose on the periphery of wafer catches up that at the center of wafer in the bias time of middle range. Therefore, even if the $R_s$ uniformity in the initial time range is degraded, the good uniformity of the $R_s$ is obtained in the entire wafer surface spontaneously after the bias time enters the middle range. Not only the precise dose controllability but also the within-wafer $R_s$ uniformity were achieved in the middle time range by utilizing the $R_s$ saturation phenomenon.
In order to confirm general relationship between ion density in plasma and within-wafer $R_s$ uniformity, ion density in plasma was measured in the PD system B. Unfortunately, it cannot be measured in the PD system A because metal contamination was strictly controlled in the PD system A for device fabrication. Figure 3.2-12 shows B dose and within-wafer $R_s$ uniformity in the PD system B. Dose rate decreased at bias time of around 10 (a.u.). The $R_s$ uniformity was improved from about 2 % at bias time of 2.5 to 1.0–1.1 % at bias time of 10. These properties of the bias time dependency are the same as those obtained in the PD system A qualitatively.

Figure 3.2-13 shows a typical example of the plasma uniformity measured at positions approximately 10 mm above from a Si wafer plane. Ion current density dropped significantly near the edge of the Si wafer and the overall uniformity was 8.8 %. $R_s$
values over a 300 mm Si wafer processed by B$_2$H$_6$ SRPD with the same plasma condition are also plotted in Fig. 3.2-13 in which the $R_s$ uniformity is 1.0 %. These results of Figs. 3.2-12 and 3.2-13 indicate that the good $R_s$ uniformity is obtained by using the B$_2$H$_6$ SRPD even if the uniformity of plasma is not so good.

![Figure 3.2-12](image)

**Figure 3.2-12:** $B$ dose and within-wafer $R_s$ uniformity as a function of bias time in the PD system B.

![Figure 3.2-13](image)

**Figure 3.2-13:** Comparison of ion current density distribution and within-wafer $R_s$ uniformity in the PD system B.

### 3.2.3 Effects of B$_2$H$_6$ mass concentration

First, the PD system A was used here, and experimental condition was almost the same as that employed in the previous experiment for Fig. 3.2-6 except for the B$_2$H$_6$
mass concentration. Although the B$_2$H$_6$ mass concentration was 0.73 mass% in the previous experiments, it was reduced from the value in this experiment. Fig. 3.2-14 shows the characteristics of bias time vs. B dose for various B$_2$H$_6$ mass concentrations. The saturation level decreased with decreasing B$_2$H$_6$ mass concentration. In these experimental conditions, absolute value of B$_2$H$_6$ concentration in process gas was very small, in which most part of process gas was composed of He, and total flow rate of the process gas was kept constant. Therefore, B$_2$H$_6$ mass concentration is proportion to B$_2$H$_6$ molar concentration (mol/L) in the chamber. As a result, the saturation level was determined by the B$_2$H$_6$ molar concentration. The mechanism of the phenomenon is understood as follows. Low B$_2$H$_6$ molar concentration results in reduced B ion implantation rate and B radical adsorption rate, but the B sputtering rate is not so changed because it is determined by He ion density and bias voltage. Thus the saturation level of B dose is lowered under the low B$_2$H$_6$ molar concentration due to the balance of these tree rates of the fundamental processes.

The similar experiment was carried out by using the PD system C. Figure 3.2-15 shows the characteristics of bias time vs. B dose for various B$_2$H$_6$ mass concentrations observed in the PD system C. The property that saturated B dose is controlled by B$_2$H$_6$ mass concentration was also obviously observed here. It was found, in this system, that B dose was decreased in long bias time range. This is probably due to wafer temperature elevated over 100 °C during the doping process because temperature control system was not equipped in the PD system C. The high temperature of wafer surface may induce high sputtering rate of B and/or low adsorption rate of B radicals, which results in deviation of the balance point. Figure 3.2-16 shows the saturated B dose as a function of B$_2$H$_6$ mass concentrations extracted from Fig. 3.2-15. It is found that the saturated B dose was precisely controlled by B$_2$H$_6$ mass concentration, which is suitable method because of well controllability of mass flow control system in general. This property is useful to obtain good controllability of both $R_s$ value and its within-wafer uniformity in B$_2$H$_6$ SRPD.
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Figure 3.2-14: B dose as a function of bias time obtained by using the PD system A. Three different $B_2H_6$ mass concentrations (low, middle, and high) were used.

Figure 3.2-15: B dose as a function of bias time obtained by using the PD system C. $B_2H_6$ mass concentration was varied from 0.025 to 0.60 mass%.

Figure 3.2-16: Saturated B dose as a function of $B_2H_6$ mass concentrations in the PD system C.
Chapter 3. Process control

3.2.4 Effects of deposition or sputtering

In PD processes, deposition of some species generated in plasma on wafers, like a chemical vapor deposition (CVD), or sputtering of wafer surface by ion bombardment from plasma often takes place obviously depending on plasma condition. These conditions are referred as “deposition rich” and “sputtering rich”, respectively, in this thesis. Considering the mechanism of the $Rs$ saturation phenomenon, these situations should affect the saturated dose in B$_2$H$_6$ SRPD.

In order to clarify which situation took place in various experimental conditions employed so far, the following experiments were carried out. Si wafers with patterned mask were prepared. These Si wafers were doped with B, in which the usual doing process was repeated 10 times or 25 times for each PD condition. After that, the patterned mask was removed. The resulted differences in surface levels between the surface area irradiated by the plasma and that covered by the mask were measured by a thickness measurement device.

The experimental conditions and obtained results are summarized in Table 3.2-1. There are two conditions referred as “case (a)” and “case (b)” as indicated in the left column. The case (a) corresponds to the condition employed in the experiment discussed in section 3.2 using PD system A. “difference in surface level” in the table represents height of surface level of plasma exposed surface measured form that of surface buried under the mask during PD process, therefore, a positive value means that something was deposited while a negative value means that original Si surface was etched by sputtering. “rate” in the table represent the deposition rate or etching rate.

Table 3.2-1: Experiments to evaluate deposition rich or sputtering rich conditions

<table>
<thead>
<tr>
<th>case</th>
<th>PD system</th>
<th>source power</th>
<th>pressure</th>
<th>$B_2H_6$ mass concentration</th>
<th>bias</th>
<th>total bias time</th>
<th>difference in surface level</th>
<th>deposition or sputtering</th>
<th>rate</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>A</td>
<td>500 W</td>
<td>0.35 Pa</td>
<td>0.73 mass%</td>
<td>250 V</td>
<td>600 s (60x10times)</td>
<td>+ 5.8 nm</td>
<td>deposition</td>
<td>0.58 nm/min</td>
<td>used in section 3.2</td>
</tr>
<tr>
<td>(b)</td>
<td>B</td>
<td>2000 W</td>
<td>0.9 Pa</td>
<td>0.05 mass%</td>
<td>135 V</td>
<td>1500 s (60x25times)</td>
<td>- 33 nm</td>
<td>sputtering</td>
<td>1.32 nm/min</td>
<td></td>
</tr>
</tbody>
</table>

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Figure 3.2-17 shows the average of $Rs$ in wafer as a function of bias time using the conditions of deposition rich (case (a)) or sputtering rich (case (b)). The $Rs$ continued to decrease for the deposition rich condition in the long time range (400-800 s), while the $Rs$ closed to the constant value asymptotically with long bias time for the sputtering rich condition. In the case of deposition rich condition, it is considered that increase in B dose due to deposition of B containing layer is larger than loss of B dose due to sputtering in the long time range. On the other hand, in the case of sputtering rich condition, the deposition with additional B dose does not take place and loss of B dose due to sputtering contributes to establish the balance state discussed previously. From the viewpoint of utilizing the $Rs$ saturation phenomenon to achieve good process controllability, B$_2$H$_6$ SRPD under the sputtering rich condition should be desirable. However, the deposition rich condition is also available provided that the dose increasing rate for bias time is sufficiently reduced.

3.3 Improvement of $Rs$ repeatability by conditioning plasma discharge method

Repeatability of $Rs$ values for every run of PD under the same condition is also a significant requirement for production lines. The first basic experiment was carried out
using the PD system B. In every PD run, pressure was 0.9 Pa, source power was 1500 W, bias power was 135 W, B₂H₆ mass concentration was 0.05 mass% and bias time was 60 s. The post annealing condition and the Rs evaluation method were the same as those used in section 3.2.

Figure 3.3-1(a) shows the average of Rs in a wafer as a function of the number of times of repeating PD process runs, and Fig. 3.3-1(b) shows an expanded view of Fig. 3.3-1(a) in which Rs value is normalized. The Rs of the wafer of first run was 1493 ohm/sq. It was doped just after the chamber cleaning maintenance, in which all deposited layer on the inner wall of the chamber had been removed. Therefore, B was doped only from introduced B₂H₆ excited by plasma discharge. The Rs was decreased with the number of the times up to around 220 ohm/sq after 400 times plasma discharges. The deposited layer was found on the inner wall of the chamber when the maintenance was carried out after 1500 times plasma discharges. The Rs decreased rapidly in the first 400 times plasma discharges, and its fluctuation run by run became small after 400 times plasma discharges. Difference between the maximum and the minimum of the averaged Rs in a wafer was within 10% during the plasma discharges from 400 to 1400 times. Therefore, good repeatability of Rs can be obtained after the several times of runs, 400 times in this case, which is referred to as “conditioning plasma discharge”. During the conditioning plasma discharge, B deposited layer is formed gradually on the inner wall of the chamber and the B₂H₆ plasma contains B not only from B₂H₆ gas but also that from the B deposited layer by sputtering as progress of the deposition. The gradual decrease in Rs during the conditioning plasma discharge is probably due to gradual extension of area of the deposited layer on the inner wall, and the following small fluctuation of Rs is probably due to saturation of the increase in area of deposited layer and due to stable steady state contributed by thick deposited layer.

Figure 3.3-2 shows the trend chart of the average of Rs and the Rs uniformity of B₂H₆ SRPD using the condition used to obtain the results shown in Fig. 3.2-10 (same as the condition of the bias time of 120 s used in Figs. 3.2-1, 3.2-7 and 3.2-9), which was obtained in the PD system A. The Rs repeatability was 0.83% with keeping the Rs
uniformity of less than 1.0 % for many runs for long term. These values are enough for the manufacturing of planar pMOSFETs. The excellent $Rs$ repeatability was achieved by the conditioning plasma discharge method discussed in this section.

![Figure 3.3-1](image1)

**Figure 3.3-1:** (a) Average of $Rs$ in wafer as a function of the number of the times of PD for conditioning plasma discharge. (b) Vertically expanded view of (a) with normalized vertical axis.

It is known that the chamber wall condition is a significant factor of process drifts leading to changes in the process performance in the field of dry etching (e.g. etch rates, etch profiles, selectivity, uniformity, etc.). Chamber wall coating methods has been well studied for the process stability of dry etching (e.g. [3.3-1]-[3.3-2]), but this study is the first time in the field of PD.

![Figure 3.3-2](image2)

**Figure 3.3-2:** Trend chart of the average of $Rs$ and the $Rs$ uniformity of $B_2H_6$ SRPD using the condition used in Fig. 3.2-10 (same as the condition of the bias time of 120 s used in Figs. 3.2-1, 3.2-7 and 3.2-9).
3.4 Conclusions

Significant results with originalities of this study obtained in this chapter are as follows:

(1) The $Rs$ saturation phenomenon was clarified and utilized to improve the dose controllability and the $Rs$ uniformity of PD.

The mechanism of the $Rs$ saturation phenomena is due to the balance of three basic processes, *i.e.*, B ion implantation, B radical adsorption and B sputtering in the middle time range of the bias time. The slow down of B dose rate in the middle time range is resulted from increase in the B sputtering rate due to increase in B surface concentration accumulated by the preceding doping during the initial time range.

The relationship that the higher surface B concentration induces the higher sputtering rate of B is useful to improving the $Rs$ uniformity. In some areas on a wafer in which dose rate is relatively higher, the drop of dose rate due to the sputtering comes earlier, and vice versa. As a result, a self-compensation mechanism works to accommodate the non-uniformity of plasma.

(2) The conditioning plasma discharge method was developed to improve the $Rs$ repeatability of PD. The manufacturing level of process controllability, *i.e.* the $Rs$ uniformity and the $Rs$ repeatability of less than 1.0 % with precise dose controllability, was demonstrated for the first time for PD.

Origin of the good $Rs$ repeatability obtained after the conditioning plasma discharge is considered that extension of area of the B deposited layer on the inner wall of the process chamber is saturated. Therefore, contribution of B from the B deposited layer by sputtering becomes constant so that the concentration of B in the $B_2H_6/He$ plasma, which contains B from both the deposited layer and the supplied $B_2H_6$ gas, becomes steady state.
The techniques developed in this chapter contributed to enable PD to have the manufacture level of process controllability for the application of USJ formation.
References


Chapter 4
Conformal doping

4.1 Introduction
4.2 Erosion of fin corners
4.3 Achievement of n-type conformal doping
4.4 Effectiveness for p-type conformal doping
4.5 Further discussions
4.6 Conclusions
4.1 Introduction

PD [4.1-1][1.4-4], epitaxial film growth [4.1-2] and various techniques [4.1-3] have been developed for conformal doping applicable to FinFETs. On the development of PD for the application, erosion of fin structures was pointed out as a significant problem [1.3-15]. The atomistic modeling of impurity I/I indicated that the maximum dose of impurity on sidewall of fins was limited by the fin erosion due to sputtering effect [4.1-4]. However, there were few reports of experimental study of PD for the erosion control. When we first applied SRPD to doping of fins, it was found that the fin corner eroded no less than 10 nm while planar Si surface was sputtered only 1 nm as shown in Fig. 4.1-1. Less controllability of the fin corner erosion was an important issue.

Another issue was difficulty in retention of sufficiently high dose on the sidewalls of fins. It was marked for n-type doping, but not so significant for p-type doping. This is due to the low adsorption efficiency of n-type dopants such as As or P on Si surfaces.

The first object in this chapter is to clarify conditions to control the erosion of fin corners during PD. The second object is to achieve conformal junction formation, especially for n-type doping, and to clarify the key parameters of the process. The mechanism of the conformal junction formation using SRPD is also discussed in this chapter.

![Figure 4.1-1: Less controllability issue of fin corner erosion in PD. (a): Sputtering for planar Si surface. (b): Erosion of fin corners.](image-url)
4.2 Erosion of fin corners

The PD system B was used for experiments in this section. Si wafers with fins were prepared by dry etching to evaluate the erosion of fins. These fins had a height of 120 nm and a width of 160 nm and were positioned in parallel with 370 nm spacing. The radius of curvature of the fin corners was 8.7 nm before PD process. These wafers with fin structures were doped with B using a B$_2$H$_6$/He plasma. Pressure and source power were varied in each plasma condition. Pressure was varied from 0.6 to 12 Pa, source power was varied from 200 to 2000 W, and bias time was varied from 20 to 400 s. Bias voltage ($V_{pp}$) was 290 V. B$_2$H$_6$ mass concentration was 0.05 mass %. Total gas flow rate was 300 cm$^3$/min. Typical implanted depth of B after these PD process was 9 nm at the B concentration of 5x10$^{18}$ cm$^{-3}$.

Ion current density and electron temperature were measured for each plasma condition by a Langmuir probe. The probe was moved with 25 mm apart from the Si substrate. They were measured at 21 points in the region between the center of Si substrate and the point of 20 mm distant from the center. Average of these measured values at 21 points was taken as the ion current density or the electron temperature. The corners curvature radii of the fins before PD and after PD were measured by using scanning electron microscopy (SEM) to evaluate the extent of corner erosion generated during the process. It was evaluated by difference in the curvature radii between before and after PD, and the small value is desirable from the viewpoint of controlling the erosion.

Figure 4.2-1(a) and (b) shows SEM images of fins before and after PD. The bias time was 200 s, pressure was 0.9 Pa, and source power was an intermediate value in the range described above. The radii of curvature of the fin corners after PD were larger than those before PD, but the height of fins was not changed. The result indicates that fin corners are easy to be eroded compared with fin top surface and it is important to control such erosions. Figure 4.2-2 shows the curvature radius of fin corner as a function of bias time, in which the other parameters were kept constant. The curvature radius was
increased with bias time linearly after the rapid increase during the initial 40 s up to 20 nm.

Figure 4.2-3 shows a boundary where the curvature radius after PD was clearly larger than twice of that before PD in the space of ion current density and pressure for bias time of 60 s. Another boundary is also shown here where the curvature radius after PD was clearly smaller than twice of that before PD. A boundary for just twice should be located between them although it cannot be specified. Ion current density is proportional to ion density in plasma. The ion density can be controlled by source power, that is, ion density is reduced with reducing source power. The increase of the curvature radius were reduced for small ion current density at the same pressure, and almost no increase of the curvature radius was observed when the pressure is lower than 0.6 Pa. Figure 4.2-4 shows the same boundaries as those observed in Fig. 4.2-3 presented in the space of electron temperature and pressure. Both boundaries were almost overlapped each other as shown in Fig. 4.2-4. Therefore it is considered that the impact from electron temperature to the erosion is much smaller than that from ion current density. Furthermore, it is observed that the increase of the curvature radius became small only by decreasing ion current density at the same pressure and the same electron temperature from Figs. 4.2-3 and 4.2-4. From these results, it is considered that the large amount of ion bombardments to fins is a dominant factor of the erosion of fin corners and that the decrease in the ion density in plasma helps to control the erosion. As a result, low source power and low pressure is desirable for controlling the erosion of fin corners.

**Fig. 4.2-1:** Cross sectional SEM images of fins (a) before PD and (b) after PD.
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Figure 4.2-2: Curvature radius of fin corner as a function of bias time.

Figure 4.2-3: Boundary where the curvature radius after PD was clearly larger than twice of that before PD, and another boundary for clearly smaller than twice, presented in the space of ion current density and pressure.

Figure 4.2-4: Boundary where the curvature radius after PD was clearly larger than twice of that before PD, and another boundary for clearly smaller than twice, presented in the space of electron temperature and pressure.
4.3 Achievement of n-type conformal doping

The PD system A was used in this section. p-type Si wafers with fins were prepared by dry etching to evaluate the resistivity conformality. These fins had a height of 120 nm and a width of 120 nm and were positioned in parallel with 220 nm spacing. Bare Si wafers without fins were also prepared to evaluate the As dose and the sheet resistance of a planar surface. These Si wafers were doped with As using an AsH₃ plasma diluted with He.

Various plasma conditions with different AsH₃ mass concentrations, pressures, and total gas flow rates were employed. The AsH₃ mass concentration was varied from 0.025 to 3.0 mass%, the pressure was varied from 0.35 to 1.2 Pa, and the total gas flow rate was varied from 30 to 800 cm³/min. Doping time was 60 s for all experiments. For the total gas flow rates of 30 and 800 cm³/min, the doping processes employed were confirmed to be the SRPD; in other words, the doping time was sufficiently long so that the sheet resistance of planar surfaces after activation annealing was nearly saturated at the end of doping [1.4-3][1.4-4]. And we are sure that all experiments were performed under the SRPD condition since it was also confirmed by other experiments that doping time at which the sheet resistance was saturated was not affected so much by these plasma conditions employed in the experiments. The plasma conditions are summarized in Table 4.3-1. Substrate temperature was 22 °C and source power was 500 W for all experiments, which were suitable values for the stable operation of the PD system. The peak to peak voltage of the bias employed here was 250 V for all experiments, which was suitable for shallow doping. After PD, the wafers were annealed by spike rapid thermal annealing (spike RTA) at 1025 °C. The spread resistance of the fins and the sheet resistance of the bare Si wafers were measured after spike RTA. The two-dimensional distributions of the spread resistance in fin cross sections were measured by SSRM. SIMS was used to measure the As dose after PD. The radii of curvature of the corners of the fins before PD and after annealing were determined by SEM in the same way as used in the previous section.
Table 4.3-1: Plasma conditions used in section 4.3.

<table>
<thead>
<tr>
<th>Plasma condition</th>
<th>AsH₃ concentration (mass%)</th>
<th>Pressure (Pa)</th>
<th>Total gas flow rate (cm³/min)</th>
<th>Source power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.35</td>
<td>30</td>
<td>500</td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
<td>0.35</td>
<td>80</td>
<td>500</td>
</tr>
<tr>
<td>C</td>
<td>0.05</td>
<td>0.40</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>D</td>
<td>0.05</td>
<td>0.50</td>
<td>440</td>
<td>500</td>
</tr>
<tr>
<td>E</td>
<td>0.05</td>
<td>0.55</td>
<td>475</td>
<td>500</td>
</tr>
<tr>
<td>F</td>
<td>0.05</td>
<td>0.65</td>
<td>540</td>
<td>500</td>
</tr>
<tr>
<td>G</td>
<td>0.025</td>
<td>0.55</td>
<td>475</td>
<td>500</td>
</tr>
<tr>
<td>H</td>
<td>0.05</td>
<td>0.55</td>
<td>475</td>
<td>250</td>
</tr>
<tr>
<td>I</td>
<td>0.5</td>
<td>0.55</td>
<td>475</td>
<td>500</td>
</tr>
<tr>
<td>J</td>
<td>1.0</td>
<td>0.55</td>
<td>475</td>
<td>500</td>
</tr>
<tr>
<td>K</td>
<td>3.0</td>
<td>0.55</td>
<td>475</td>
<td>500</td>
</tr>
<tr>
<td>L</td>
<td>5.0</td>
<td>0.55</td>
<td>475</td>
<td>500</td>
</tr>
<tr>
<td>M</td>
<td>0.14</td>
<td>1.2</td>
<td>800</td>
<td>500</td>
</tr>
</tbody>
</table>

Figure 4.3-1 shows the spread resistances of the fin sidewall and the fin top surface as a function of the total gas flow rate. AsH₃ mass concentrations used in this work were 3 values in the range 0.05 to 0.8 mass%, and they are represented by the symbols indicated in the inset of the figure for the conditions of total gas flow rate. The pressure was increased in the range between 0.35 and 1.2 Pa according to the increase of the total gas flow rate. The result is discussed for the lower total gas flow rates (30-300 cm³/min) and for the higher total gas flow rates (440-800 cm³/min) separately as follows.

We first compare the results obtained at total gas flow rates of 30 and 300 cm³/min. The fin top surface had a spread resistance as low as 3×10⁴ ohm at the lowest total gas flow rate of 30 cm³/min. In contrast, the fin sidewall exhibited an extremely high resistance at the same total gas flow rate, which indicates that the As dose was very low on the fin sidewall. The AsH₃ mass concentration was reduced when the total gas flow rate was 300 cm³/min so as to give the same As dose on a planar Si surface as that when the total gas flow rate was 30 cm³/min (8×10¹⁴ cm⁻²). This resulted in the fin top surfaces having almost the same spread resistances for total gas flow rates between 30
and 300 cm³/min. Just as was observed for the fin top surface, the spread resistance of the fin sidewall decreased at higher total gas flow rates even when the reduced measurement precision of SSRM at such high resistivity regions is considered. Based on these results, it is considered that increasing the total gas flow rate increases the As dose on the fin sidewall and that the increase in the As dose is greater on the fin sidewall than that on the fin top surface.

The resistivity of the fin sidewall continued to decrease at higher total gas flow rates between 440 and 540 cm³/min, in which the AsH₃ mass concentration was kept constant at 0.05 mass%. In this region, the resistivity of fin top surface also decreased at the same rate. The ratio of the spread resistance of the fin sidewall to that of the fin top surface was still high, being between 3.2 and 2.7. At an even higher total gas flow rate of 800 cm³/min, in which the AsH₃ mass concentration was increased to 0.14 mass%, the spread resistances of both the fin sidewall and the fin top surface were very low and were almost the same as each other. This indicates that conformal doping was achieved at a total gas flow rate of 800 cm³/min.

![Figure 4.3-1: Spread resistance of fin sidewall and fin top surface as a function of total gas flow rate. Three different AsH₃ mass concentrations, between 0.05 and 0.80 mass%, were used.](image-url)
Figure 4.3-2 shows the spread resistances of the fin sidewall and the fin top surface as a function of the AsH₃ mass concentration. Other process parameters besides the AsH₃ mass concentration were kept constant. The total gas flow rate was fixed at 475 cm³/min. In Fig. 4.3-1, the AsH₃ mass concentration at a total gas flow rate of 475 cm³/min is 0.05 mass%. The spread resistance of the fin top surface had a lowest value of $3 \times 10^3$ ohm. In contrast, the spread resistance of the fin sidewall saturated at $8 \times 10^3$ ohm so that it did not have the minimum value. In these cases, the ratio of the spread resistance of the fin sidewall to that of the fin top surface was as high as 2.5. This indicates that conformal doping cannot be achieved only by increasing the AsH₃ mass concentration. A total gas flow rate as high as 800 cm³/min is required to realize conformal doping, as shown in Fig. 4.3-1.

For spike RTA at 1025°C, the spread resistance of the fin top surface decreased to $3.4 \times 10^3$ ohm at a total gas flow rate of 800 cm³/min, as shown in Fig. 4.3-1. For this condition, the As dose was evaluated by SIMS and found to be $9.4 \times 10^{15}$ cm⁻². The fact that the As dose for the top surfaces with spread resistances of about $3 \times 10^3$ ohm (see Figs. 4.3-1 and 4.3-2) ranged between $9.4 \times 10^{15}$ and $1.7 \times 10^{16}$ cm⁻² indicates that the amount of activated As is almost the same even when the As dose is increased above $9 \times 10^{15}$ cm⁻². It is well known that resistivity cannot be decreased lower than a limited value decided by a maximum concentration of electrically activated dopant atoms even if surplus dopant atoms are introduced. The observed lower limit of the spread resistance, about $3 \times 10^3$ ohm (350 ohm/sq. using planar Si wafer measured by four point probe) is considered to correspond to the limited resistivity correlated with the saturation of electrical activation. Therefore, the conformality has been realized by the high As dose on the sidewall enough to provide the As concentration for the saturated electrical activation.

Figure 4.3-3(a) shows a SSRM image of the sample doped at a total gas flow rate of 800 cm³/min (see Fig. 4.3-1). Figure 4.3-3(b) shows a depth profile of the spread resistance along line a1 indicated in Fig. 4.3-3(a). The lowest spread resistance below the fin top surface, $3.4 \times 10^3$ ohm, is found at a depth between 2 and 21 nm. The length from the fin top surface to the point at which the spreading resistance increases to $6.8 \times 10^3$ ohm
(twice as much as the lowest value) on line a1 is 26 nm. This is a reasonable criterion for estimating the junction depth since the length (26 nm) is almost the same as the junction depth (defined as the depth at which the As concentration is $5 \times 10^{18}$ cm$^{-3}$ after annealing) of 25 nm measured by SIMS for a bare Si wafer. Figure 4.3-3(c) shows depth profiles of the spread resistance along line a2 indicated in Fig. 4.3-3(a) and Fig. 4.3-3(d) shows an expanded view of Fig. 4.3-3(c) for the region near the surface of a sidewall. The region with the lowest spread resistance on the fin sidewall is located near 640 nm from a2 (see Fig. 4.3-3(c)). This region has a spread resistance of $2.9 \times 10^3$ ohm and the length from the right side surface of the fin (650 nm from a2) to the point at which the spreading resistance increases to $6.8 \times 10^3$ ohm (626 nm from a2) is 24 nm. This length of 24 nm is considered to correspond to the junction depth of the doped layer on the fin sidewall. From these results, the ratio of the spread resistance of the fin sidewall to that of the fin top surface is estimated to be almost 1 ($2.9 \times 10^3$ ohm / $3.4 \times 10^3$ ohm = 0.85), which indicates that conformal doping was realized. This resistivity conformality is much better than the previous best value for ion implantation of 2. Furthermore, the ratio of the junction depth of the fin sidewall to that of the fin top surface is also close to 1 (24 nm/26 nm = 0.92). From the spread resistance ratio and the junction depth ratio, we can determine the ratio of the sheet resistance of the fin sidewall to that of the fin top surface to be close to 1 ($0.85/0.92 = 0.92$). The sheet resistance measured by a four-point probe on a bare Si wafer was 348 ohm/sq. Therefore, the sheet resistances of the fin top surface and the fin sidewall are considered to be approximately the same as this value at a total gas flow rate of 800 cm$^3$/min. In the ITRS2010 update, the requirement for maximum drain extension sheet resistances for multi-gate MPU/ASIC (NMOS) are 441 ohm/sq for year 2015 and 475–691 ohm/sq for years 2016–2020 [1.2-1]. Thus, the sheet resistance obtained in this study is suitable for n-channel FinFETs.
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Figure 4.3-2: Spread resistances of fin sidewall and fin top surface as a function of AsH₃ mass concentration. The horizontal dotted line indicates the lower limit of the spread resistance obtained from the annealing conditions used in this section.

Figure 4.3-3: Spread resistances measured by SSRM for As doped sample fabricated using a total gas flow rate of 800 cm³/min (see Fig. 4.3-1). (a): SSRM image. (b): Spread resistance profile along line a1. (c): Spread resistance profile along line a2. (d): Enlargement of (c).
To determine the essential factors for realizing conformal doping, the gas residence time and the molar concentrations of AsH$_3$ and He were calculated from the plasma parameters. The gas residence time $T$ was calculated using:

$$ T = \frac{VP}{Q}, $\tag{1}$$

where $V$ denotes the vacuum chamber volume, $P$ is the pressure, and $Q$ is the total gas flow rate. The AsH$_3$ and He flow rates were calculated using the AsH$_3$ mass concentration in the AsH$_3$/He mixture gas cylinder and the flow rates of AsH$_3$/He mixture gas and He gas in which the He flow rate was the sum of the effective flow rate of the He fraction from the AsH$_3$/He mixture gas cylinder and the flow rate from a pure He gas cylinder. Based on these parameters, the molar concentrations (mol/L) of AsH$_3$ and He in the chamber were derived using the gas flow rates of both gases, $T$, and $V$. These AsH$_3$ and He molar concentrations represent the AsH$_3$ and He concentrations in the vacuum chamber when the pressure is controlled to be constant during PD.

Figure 4.3-4 shows the spread resistance of the fin sidewall plotted at different AsH$_3$ molar concentrations and gas residence times. A sufficiently high AsH$_3$ molar concentration (of the order of $10^{-11}$ mol/L or greater in this experiment) is required to obtain a low spread resistance. In addition, a short gas residence time (shorter than 100 ms in this experiment) is essential, even when a sufficiently high AsH$_3$ molar concentration is used. As Eq. 1 indicates, the short gas residence time is due to the high total gas flow rate (as discussed above in relation with Figs. 4.3-1 and 4.3-2). This result indicates that only some species, such as AsH$_3$ radicals (but not neutral AsH$_3$ molecules), increase the As dose in the fin sidewall and that these species have finite decomposition times. Excessively decomposed species, such as AsH$_x$ radicals and/or ions with small $x$, are not considered to contribute to doping of the fin sidewall. A short gas residence time is expected to realize high concentrations of the effective species since they reach the fin sidewall before they decompose.

Figure 4.3-5 shows the spread resistance of the fin sidewall plotted at different AsH$_3$ and He molar concentrations. The all experimental data shown in Fig. 4.3-4 are repotted again in Fig. 4.3-5 as a function of He molar concentrations as well as that of
AsH₃ molar concentration. The circular and triangular symbols in Figs. 4.3-4 and 4.3-4 have almost the same gas residence times (less than 100 ms), whereas the circular symbols have a lower AsH₃ molar concentration than the triangular symbols in these figures. However, the circular symbols clearly have a lower spread resistance in the fin sidewall than the triangular symbols and the circular symbols have a higher He molar concentration than the triangular symbols. These results suggest that both high AsH₃ and He molar concentrations are required for short gas residence times to realize conformal doping. A high He molar concentration results in high He and AsHₓ ion densities; these ions can sputter As films deposited on the inner wall of the vacuum chamber. Although the mechanisms for the increase in the dose induced by a high He molar concentration are currently not clear, it is speculated that these phenomena contribute to the dose enhancement on the fin sidewalls.

The pressure is varied depending on the total gas flow rate relating to the AsH₃ and He molar concentrations in these experiments. The high total gas flow rate resulted in high pressure since evacuation speed of the PD system is limited. Therefore, the best conformal doping was achieved at the highest pressure in our experiments. It may be necessary to consider the direct effects of the high pressure, such as short mean free path of dopant species in the plasma. However, the high pressure is not probably essential condition to achieve the conformality as far as the above discussions. The short gas residence time due to the large total gas flow rate and the high molar concentration of both AsH₃ and He are essential conditions to obtain the high As dose on the sidewall so that the conformal doping is realized.

Fin erosion during PD is a general problem [1.3-14][1.4-4]. Deformation of fin due to the erosion affects device characteristics harmfully. Figure 4.3-6 shows the relationship between the increase in the radius of curvature of the fin corners during PD and spike RTA and the spread resistance of fin sidewall. It shows that there is a trade-off relationship. The radius of curvature of fin corners increases with increasing PD working pressure [1.4-4]. On the other hand, a high total gas flow rate is a necessary to realize conformal doping (as discussed above). However, the exhaust speeds of evacuation
systems in practical PD systems are limited. Therefore, it is necessary to employ higher pressures to realize higher total gas flow rates. This is the origin of the trade-off relationship shown in Fig. 4.3-6. In practical operation, it is necessary to optimize the total gas flow rate to suppress degradation of device characteristics.

**Figure 4.3-4:** Spread resistance of fin sidewall as functions of AsH₃ molar concentration and gas residence time. The spread resistance was divided into four levels as indicated in the legend.

**Figure 4.3-5:** Spread resistance of fin sidewall as functions of AsH₃ and He molar concentrations. The spread resistance was divided into four levels as indicated in the legend.
n-type SRPD under the condition of the total gas flow rate of 800 cm³/minute was employed to fabricate nMOS FinFETs. The $I_{ON}$ enhancement by 10% at the same drain induced barrier lowering (DIBL) was achieved by combining the n-type SRPD and the dual annealing in imec device lot [1.4-6]. It was also reported in [1.4-6] that this high device performance resulted from 40% reduced external resistance relative to the ion implantation process as a reference. The demonstrated $I_{ON}$ of 1.23 mA/µm for $I_{OFF} = 100$ nA/µm at 1 V is highly compatible to the state of the art FinFET devices found in literatures [1.4-7][1.2-8]. However, the problem of long diffusion length of As due to the dual annealing scheme is pointed out. This long diffusion length leads poor short channel effect. The integration problem for reducing short channel effect is remained.

### 4.4 Effectiveness for p-type conformal doping

Purpose of this section is to confirm whether the technique used for n-type
conformal doping discussed in the section 4.3 is also effective in p-type conformal doping. In experiment, n-type Si wafers with fins were prepared by dry etching to evaluate the conformality of resistivity. These fins had a height of 120 nm and a width of 120 nm and were positioned in parallel with 220 nm spacing. Bare Si wafers without fins were also prepared to evaluate the sheet resistance of a planar surface. These Si wafers were doped with B using a B$_2$H$_6$/He plasma.

Two plasma conditions of different B$_2$H$_6$ mass concentrations, pressures, and total gas flow rates were employed. In the first condition, B$_2$H$_6$ mass concentration was 0.73 mass%, pressure was 0.35 Pa and total gas flow rate was 33 cm$^3$/min. In the second condition, B$_2$H$_6$ mass concentration was almost the same, pressure was almost 2 times higher than 0.35 Pa and total gas flow rate was 345 cm$^3$/min (around ten times larger than 33 cm$^3$/min). For the first condition, the doping process was confirmed to be the SRPD. The doping time was 60 s, it is so long that the sheet resistance of planar surfaces after activation annealing was nearly saturated at the end of doping [1.4-2][1.4-3].

After PD, the wafers were annealed by spike RTA at 1000°C. The spread resistance of the fins and the sheet resistance of the bare Si wafers were measured after the spike RTA. The two-dimensional distributions of spread resistance in the fin cross sections were measured by SSRM. The radii of curvature of the fin corners, before PD and after annealing, were measured by SEM.

Figure 4.4-1(a) shows the SSRM image for the sample doped by the first condition, in which gas residence time was 586 ms, B$_2$H$_6$ mol concentration was 1.63x10$^{-10}$ mol/L and He mol concentration was 1.54x10$^{-7}$ mol/L. Figure 4.4-1(b) shows depth profiles of the spread resistance along the line A1 and A2 indicated in Fig. 4.4-1(a). The lowest spread resistance under the fin top surface, 1.84x10$^4$ ohm, was found at the depth between 5 nm and 10 nm. Figure 4.4-1(c) shows depth profiles of the spread resistance along the line A3 indicated in Fig. 4.4-1(a). The region of the lowest spread resistance on the fin sidewall is found at around the position of 630 nm as shown in Fig. 4.4-1(c). The spread resistance in this region is 1.97x10$^4$ ohm. From these results, the ratio of the spread resistance of fin sidewall to that of fin top surface is evaluated to be
1.07 (1.97x10⁴ ohm/1.84x10⁴ ohm = 1.07). This conformality of resistivity is much better than the previous best value for I/I, i.e., 2. Sheet resistance measured by four-point probe on the bear Si wafer was 1314 ohm/sq. In case of p-type doping, the conformality of resistivity closed to 1 (1.07) was realized even when the gas residence time was much longer than 100 ms (586 ms). However, the resistivity and the sheet resistance were not low enough to enhance the on current of pMOS FinFETs. Thus, resistivity on fin sidewall lower than this result was required.

Figure 4.4-2(a) shows the SSRM image for the sample doped under the second condition, in which gas residence time was markedly reduced shorter than 100 ms, mol concentrations of B₂H₆ and He were around 10 % and 50%, respectively, higher than those in the first condition. Figure 4.4-2(b) shows depth profiles of the spread resistance along the line B1 and B2 indicated in Fig. 4.4-2(a). The lowest spread resistance under the fin top surface, 1.1x10⁴ ohm, was found at the depth between 2 nm and 20 nm. Figure 4.4-2(c) shows the depth profiles of the spread resistance along the line B3 indicated in Fig. 4.4-2(a). The region of the lowest spread resistance on the fin sidewall is found at around the position of 110 nm as shown in Fig. 4.4-2(c). The spread resistance in this region is 1.1x10⁴ ohm. From these results, the ratio of the spread resistance of fin sidewall to that of fin top surface is evaluated to be very close to 1 (1.1x10⁴ ohm/1.1x10⁴ ohm = 1.0), which indicates that the conformal doping is realized. Sheet resistance measured by four-point probe on the bear Si wafer was 910 ohm/sq. The sheet resistance for the total gas flow rate of 345 cm³/min (the second condition) was 30 % lower than that for the total gas flow rate of 33 cm³/min (the first condition). In the ITRS2010 update, the requirement for maximum drain extension sheet resistance for multi-gate MPU/ASIC (PMOS) are 970 ohm/sq at year 2015 and 1045-1520 ohm/sq at year 2016-2020 [1.2-1]. The sheet resistance obtained in this work is suitable for these pMOS FinFETs. Referring the results shown in Figs. 4.3-4 and 4.3-5, the B₂H₆ mol concentration in the first condition is considered to be already sufficiently high, and it is considered that the short gas residence time and the large mol concentrations of He in the second condition brings low resistivity and low sheet resistance in fin sidewalls. From
these results, it is confirmed that the technique used for n-type conformal doping discussed in the section 4.3 is effective also in p-type conformal doping.

![Figure 4.4-1: Cross sectional profile of spread resistances measured by SSRM for B doped sample fabricated using a total gas flow rate of 33 cm³/min. (a): SSRM image. (b): Spread resistance profiles along lines A1 and A2. (c): Spread resistance profile along line A3.](image1)

![Figure 4.4-2: Cross sectional profile of spread resistances measured by SSRM for B doped sample fabricated using a total gas flow rate of 345 cm³/min. (a): SSRM image. (b): Spread resistance profiles along lines B1 and B2. (c): Spread resistance profile along line B3.](image2)

**4.5 Further discussions**

In this section, considerations are added about several questions. 1) Why do impurities enter in fin sidewalls? Is it deposition or ion implantation? 2) What is expected when the aspect ratio of fin interval and fin height is large, e.g. 1:3? Is it still possible to
1) Why do impurities enter in fin sidewalls? Is it due to deposition or ion implantation?

As discussed in section 4.3, the fact that sufficiently high AsH$_3$ molar concentration and short gas residence time are essential factors for higher dose on fin sidewalls suggests that some As-containing radicals are dopant source for fin sidewall. Therefore, not ion implantation but deposition or adsorption of these radicals on fin sidewall surface is considered to provide the sidewall doping since radicals are electrically neutral. However, sufficiently high He molar concentration is also essential factor. It is known that most of ions have incident angles less than 10 degree at low pressures in plasma (e.g. 1.3 Pa in [4.5-1] and 0.93 Pa in [4.5-2]) where the incident angle is defined as the angle between the direction of an incident ion and the normal to the upper surface of Si wafer as shown in Fig. 4.5-1. This is because collision frequency of ions in sheath becomes low [4.5-2]. In the case of ICP plasma (Ar-O$_2$ plasma), the number of ions having the incident angle of 3 degree was ten times smaller than that of 0-0.76 degree at pressures of 0.53-0.93 Pa (4-7 mTorr) [4.5-1]. The range of pressure used in this study was 0.35-1.2 Pa (2.6-9 mTorr) as shown in Table 4.3-1, so the incident angle distribution should resemble to the cases of these reports. Ions having such small incident angle impinge sidewalls with small incident angle, in other words, with glancing angle. And, the high He molar concentration should provide large flux of He ions with glancing angle incidence on fin sidewalls. Therefore, a possible process of sidewall doping is a synergistic effect of the deposition or adsorption of the As-containing radicals and the He ion bombardment with glancing angle as discussed later in 4.5 3). This process would help to enhance retention of As in the near surface region of fin sidewalls.
2) What is expected when the aspect ratio of fin interval and fin height is large, e.g. 1:3? Is it still possible to dope impurity in sidewalls?

Doping to fin sidewalls is considered to be still possible for SRPD even for such high aspect ratio, because both necessary radicals and ions reach fin sidewalls. Flux of radicals to fin sidewall per unit time should be reduced due to small solid angle in the case of high aspect ratio, but a longer bias time will solve the problem. The long bias time reduces the resistivity of fin sidewall up to the lower limit of resistivity decided by annealing condition, and good conformality would be obtained. Since He ions in plasma have small incident angle (generally lower than 3-10 degree [4.5-1][4.5-2]), the flux of ions to fin sidewalls per unit time is not so changed even for high aspect ratio, e.g. 1:3.

3) What is the difference between SRPD process and conventional deposition processes?

First, the deposited layer by SRPD would be thinner than that by the conventional deposition processes. Second, a part of radicals adsorbed on the fin sidewall would be pushed into the very shallow region under the sidewall surface by knocking on process by He ion bombardments during SRPD. It is considered that radical adsorptions and knocking on process take place simultaneously during SRPD. On the other hand, the knocking on process does not occur generally in conventional deposition processes.
4.6 Conclusions

Significant results with originalities of this study obtained in this chapter are as follows:

1) Guiding principle to control the erosion of fin corners during PD was proposed. Since ion bombardment is a dominant factor, the decrease of ion density in plasma is effective to control the erosion. In order to realize the condition, small source power and low total pressure are desirable.

2) The SRPD method suitable to form conformal junction was developed, in which the radical adsorption and the self-regulated characteristics of $R_s$ were utilized. For the first time, the excellent conformality of the resistivity ratio of 1 was achieved for n-type doping. This method and concept was effective not only for n-type conformal doping but also for p-type conformal doping.

Advantage of the conformal doping technique was demonstrated by the performance of nMOS FinFETs in which this technique was applied. $I_{ON}$ enhancement of nMOS FinFETs by 10% at the same DIBL was achieved. The demonstrated $I_{ON}$ of 1.23 mA/µm for $I_{OFF} = 100$ nA/µm at 1 V is highly compatible to the state of the art FinFET device found in literature [1.4-7][1.2-8].

3) Key parameters of the SRPD for forming n-type conformal junction were clarified. A high total gas flow rate and a high AsH$_3$ concentration, which reduce the resistivity of the fin sidewall, were found to be significant process conditions for realizing conformal doping. A short gas residence time and high molar concentrations of AsH$_3$ and He in the process chamber were found to be essential physical parameters, since they provide large amounts of dopant species with finite decomposition times. By utilizing such conditions, a sufficient large amount of As is supplied to both top and sidewall surfaces so that the lowest resistivity is uniformly obtained in these regions because the concentration of
activated As is saturated even when surplus As is supplied to the fin surfaces.

In practical PD process systems, optimization of the total gas flow rate is necessary due to the trade-off relationship between conformality and fin erosion.
Chapter 4. Conformal doping

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Chapter 5

Conclusions
In this thesis, PD has been experimentally investigated as a promising candidate to solve the problems concerned with source/drain extension formation for scaled planar MOSFETs and three-dimensional MuGFETs.

The contributions of this work can be divided into three main subjects:
1. Study of USJ formation for scaled planar MOSFETs using PD (Chapter 2).
2. Study of the process control of PD for USJ formation (Chapter 3).
3. Study of conformal junction formation for MuGFETs using PD (Chapter 4).

In Chapter 2, He PD was introduced for source/drain extension formation. He PD produced well-defined amorphous layers with desirable optical absorption properties for activation annealing. The B$_2$H$_6$ PD with preceding He PD method produced shallow, high B concentration and steep as-doped B profiles. The sub-10 nm USJ formation with low $R_s$ was achieved after laser annealing by using this method. This is the first-time demonstration of sub-10 nm USJs with particularly low $R_s$ fabricated by PD.

SRPD (self-regulatory plasma doping), i.e., PD using high He mass concentration and long bias time, was proposed. Surface amorphous layers on Si wafers were formed also in SRPD process since He concentration in the near surface region exceeded a threshold value for amorphization during the long bias time, in spite of reduced ion current density due to the B$_2$H$_6$ mixture. A p-type USJ with $X_f$ shallower than 10 nm (8.3 nm) with the low $R_s$ of 1450 ohm/sq was achieved after FLA. $I_{ON}$ of planar pMOSFETs ($L_g$= 80 nm) was increased by 14 % at the $I_{OFF}$ of 10$^{-8}$ A/$\mu$m and by 26 % at $I_{OFF}$ of 10$^{-9}$ A/$\mu$m by introducing B$_2$H$_6$ SRPD compared to that by using conventional I/I. These results indicate the potential of PD to enhance performance of scaled planar pMOSFETs.

In Chapter 3, $R_s$ uniformity, $R_s$ controllability and $R_s$ repeatability were improved by utilizing the $R_s$ saturation phenomenon and the conditioning plasma discharge method. It was demonstrated for the first time that the process controllability required for manufacturing (the $R_s$ uniformity and the $R_s$ repeatability of less than 1.0 %
with precise dose controllability) was achieved in PD.

The $Rs$ saturation phenomenon was discussed on the bias time ranges divided in three zones such as initial, middle and long time ranges, and its mechanism was understood to be a balance of B ion implantation, B radical adsorption and B sputtering in the middle time range. That is, the slow down of B dose rate in the middle time range is resulted from increase in the B sputtering rate due to increase in B surface concentration accumulated by the preceding doping during the initial time range. This mechanism works effectively for improving the $Rs$ uniformity due to a negative feedback compensating special non-uniformity of plasma, and it works also for improving the $Rs$ controllability realized simply by bias time owing to the dose change relatively insensitive to bias time in the middle and long time ranges.

The small wafer-to-wafer distribution of $Rs$, i.e., good repeatability, was realized after the conditioning plasma discharge process. This is considered that the increase in area of the B deposited layer on the inner wall of the chamber is saturated so that B concentration in B$_2$H$_6$/He plasma is stabilized.

The techniques developed in Chapter 3 enabled PD to have the process controllability with manufacture level for the application of USJ formation.

In Chapter 4, PD method to form conformal junctions by enhancing efficiency of radical adsorption was developed. Excellent conformity in which the ratio of the resistivity of fin sidewall to that of the fin top surface was very close to 1 was achieved for not only p-type doping but also n-type doping. The conformal junction formation by n-type PD was demonstrated for the first time. The key parameters of the n-type PD for conformal junctions were clarified. A short gas residence time and high molar concentrations of AsH$_3$ and He in the process chamber were found to be essential physical parameters, since they provide large amounts of dopant species with finite decomposition times. By utilizing such conditions, a sufficient large amount of As is supplied to both the top and sidewall surfaces so that the lowest resistivity is uniformly obtained in these regions because the concentration of activated As is saturated even
when surplus As is supplied to the fin surfaces.

Process condition to control the erosion of fin corners during PD was proposed, which has been another significant issue for the FinFET applications. Since ion bombardment is a dominant factor, the decrease of ion density in plasma is effective to control the erosion. In order to realize the condition, small source power and low total pressure are desirable.

Advantage of the conformal doping technique was demonstrated by the performance of nMOS FinFETs. $I_{ON}$ enhancement on nMOS FinFETs by 10% at the same DIBL was realized by combining the n-type SRPD developed in this study and the dual annealing process in imec device lot. The demonstrated $I_{ON}$ of 1.23 mA/µm for $I_{OFF} = 100$ nA/µm at 1 V is highly compatible to the state of the art FinFET devices found in literature [1,4-7][1,2-8]. However, the problem of long diffusion length of As due to the dual annealing scheme is pointed out. This long diffusion length leads poor short channel effect. The integration problem for reducing short channel effect is remained when the SRPD is applied to scaled FinFETs. In order to solve this problem, deeper understanding of the SRPD is useful.

In conclusion, the studies in this thesis provide the useful process techniques and the further understanding of PD to enable fabrication of USJs and conformal junctions for practical manufacturing. These studies are expected to contribute to the future progress of LSI process technology.
Chapter 5. Conclusions

Publications and Presentations

[Publications as 1st author]

[Presentations as 1st author, International conference]

[Presentations as 1st author, in Japan]
Chapter 5. Conclusions


**[Publication of Panasonic in-house journal as 1st author]**


**[Publications as co-author]**


**[Presentations as co-author, International conference]**


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[Presentations as co-author, in Japan]


[Patents]
19 registrations of US patent, 9 registrations of Japanese patent
Award

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