Characterization of Microscopic Uniformity of Semi-Insulating GaAs Substrate by Using High Density FET Array

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Microscopic uniformity of MESFET properties fabricated by the direct ion implantation into semi-insulating GaAs substrates is discussed by using an advanced high density FET array configuration. The pitch of FET array is 60μm x 60μm. Clear network pattern and slip line pattern of V\text{th} distributions were observed in the center and the edge of an undoped LEC substrate, respectively. On the other hand, in the region where only the isolated dislocations exist, V\text{th} is uniform. Combined with the microscopic K-value distribution and gamma value distribution, it was clarified that the residual acceptor concentration is low in the region of clustered dislocations.

1. Introduction

To fabricate GaAs LSIs with high yield, the properties of individual MESFET must be highly uniform. However, when the MESFETs are fabricated by the direct ion implantation into liquid encapsulated Czochralski (LEC) semi-insulating substrate, it is well known that the uniformity of threshold voltage (V\text{th}) of MESFET depends on the quality of the semi-insulating substrate.

Several works on the relation between V\text{th} and dislocation density have been reported. From the macroscopic V\text{th} distribution, M-shaped distribution corresponds to the W-shaped distribution of dislocation density has been observed. However, since the macroscopic V\text{th} distribution greatly depends on the FET fabrication process, it is difficult and incorrect to characterize the substrate quality by the macroscopic V\text{th} distribution.

Some discussions of more microscopic V\text{th} distribution were reported recently. Miyazawa et al reported that the V\text{th} was strongly influenced by the distance between a dislocation and an FET. On the contrary, Winston et al claimed that there was no correlation between the distance and a V\text{th}. Takebe et al showed the two-dimensional V\text{th} map of large number of FETs with 200μm x 200μm pitch. The dislocation induced network pattern was observed vaguely. Matsuoka et al fabricated a 10x10 FET array with 40μm x 40μm pitch and showed a microscopic correlation between V\text{th} and clustered dislocations.

The reason why the clear discussions of microscopic uniformity have not been performed is thought to be the lack of FET density and/or the limitation in the FET number. The major bottleneck for the increasing of FET density and number is the large area of pads for probing needle. We solved this problem by using advanced FET array configuration. In this paper, after explaining this array pattern, the relation between V\text{th} and dislocations are clearly discussed on the basis of the data of microscopic V\text{th} distribution.

2. FET Array Pattern

The FET array pattern used in this study is shown in Fig.1. The pad size is 50μm x 50μm and the FET interval is 60μm x 60μm. Each pad is
Fig. 2 The equivalent circuits of (b) an FET, (c) a two dimensional FET array, and (d) the FET to be measured and surrounding FETs.

commonly used by surrounding three FETs. In this pattern, only one pad is needed for one FET.

The reason why correct FET properties can be measured using such a common pad pattern is as follows (see Fig. 2). A MESFET can be expressed by diodes and a resistor as shown in Fig. 2(b). Then, the FET array can be written as Fig. 2(c). So, the equivalent circuit of the FET to be measured and surrounding FETs is expressed as Fig. 2(d). When $V_{th}$ is measured, drain-gate and drain-source fringing diodes are reverse biased. So, the surrounding FETs do not affect drain current ($I_d$), and therefore, correct FET properties except for Schottky properties can be measured.

By using this array pattern, the density of FET can be increased to 277 FETs/mm$^2$, which is about one order higher than that of a conventional pattern. This density is comparable to the actual FET density in GaAs LSIs. Compared with the pattern in Ref. (6), fabrication process is simple and the number of FETs is not limited because 2nd level interconnection is not needed.

3. Sample Preparation and Measuring

FETs were fabricated by ion implantation into semi-insulating substrates using a conventional refractory metal gate self-alignment process.

Table I Major process conditions used in this study.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Implants</th>
<th>Energy (keV)</th>
<th>Dose (x10$^{12}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Si</td>
<td>6.0</td>
<td>1.2</td>
</tr>
<tr>
<td>n$^+$</td>
<td>Si</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Annealing</td>
<td>Capless in AsH$_3$ atmosphere</td>
<td>800°C</td>
<td>20 min</td>
</tr>
<tr>
<td>Gate metal</td>
<td>W-Al(1at.%)</td>
<td>1000Å</td>
<td></td>
</tr>
<tr>
<td>Gate length</td>
<td>1.5 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gate width</td>
<td>10 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of FETs</td>
<td>700</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Major processing parameters are summarized in Table I. Two kinds of substrates were examined. One is a commercially available undoped LEC substrate (2-inch diameter) and the other is an MOCD-grown undoped buffer layer on a Horizontal Bridgman (HB) substrate (an MO-substrate$^7$).

FET properties were measured using computer controlled probing system. The $V_{th}$ and the K-value were calculated by the $I_d$ equation at $V_d=1V$. The gamma value was calculated by the $V_{th}$ ($V_d=1V$) and $V_{th}$ ($V_d=2V$) using the equation of $V_{th}$.

4. Threshold Voltage Distribution

Figure 3 shows the examples of two-dimensional $V_{th}$ distribution displays of 700 FETs in some wafer regions. The step of $V_{th}$ is 20mV. In the central region of an undoped LEC substrate (Fig. 3(a)), a clear network pattern having a dimension of 0.5-1.0 mm was observed. Evidently, this network pattern corresponds to the dislocation network pattern. In the cell wall region, where dislocations are clustered, the $V_{th}$ was 50-100 mV lower than the other. In the doughnut region (the midway between center and wafer edge), the $V_{th}$ distribution was very uniform as shown in Fig. 3(b), although isolated dislocations of about 2x10$^4$ cm$^{-2}$ exist. In the wafer edge region (Fig. 3(c)), clear slip line pattern of 100-200 μm width, where $V_{th}$ is 50-100 mV lower than the other can be seen. On the other hand, the uniformity of MO-substrate, in which the isolated dislocations of about 5x10$^3$ cm$^{-2}$ exist, is excellent as shown in Fig. 3(d). The mean values and standard deviations of $V_{th}$ in the above regions are summarized in Table II.
5. Gamma Value and K-Value Distribution

Figure 4 shows the distribution maps of gamma value and K-value in the central region of undoped LEC substrate (the same region as Fig.3(a)). Although the contrast is weaker than that of $V_{th}$, the distinct network patterns can be also observed. In the cell wall region, gamma value is large and K-value is small.

The microscopic gamma distribution has not yet been reported. The K-value distribution in undoped LEC substrate has been reported in Ref. (5), in which no correlation between K-value and dislocations was observed. The distinct correlation between K-value and the dislocation density in Fig.4(b) is in contrast with the result of Ref.(5).

6. Discussion

From the results of microscopic $V_{th}$ distribution, it is clear that the clustered dislocations such as dislocation networks and slip lines affect the $V_{th}$. Isolated dislocations did not affect $V_{th}$ even when the density of which was $2 \times 10^4 \text{ cm}^{-2}$. In the region of clustered dislocations, $V_{th}$ is low, K-value is low, and gamma value is high.

These relations are clearly shown in Fig.5 and 6. Figure 5(a) and (b) show the correlation between K-value and $V_{th}$ in the LEC doughnut region.

Table II Mean values and standard deviations of $V_{th}$ of 700 FETs in some wafer regions.

<table>
<thead>
<tr>
<th>Substrate and</th>
<th>Mean value (mV)</th>
<th>Standard deviation (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEC Center</td>
<td>+104</td>
<td>34</td>
</tr>
<tr>
<td>LEC Doughnut</td>
<td>+130</td>
<td>14</td>
</tr>
<tr>
<td>LEC Edge</td>
<td>+117</td>
<td>26</td>
</tr>
<tr>
<td>NO Center</td>
<td>+231</td>
<td>11</td>
</tr>
</tbody>
</table>
Fig. 5 The correlation between K-value and $V_{th}$ in the central region of the undoped LEC substrate.

and the LEC center region, respectively. In the LEC doughnut region, where $V_{th}$ is uniform, no correlation between K-value and $V_{th}$ is observed. On the other hand, there is a clear positive correlation in the LEC center region. The K-value dependence on $V_{th}$ is far larger than that obtained from the dose dependence of Si ion implantation. In Fig. 6, a negative correlation between gamma value and $V_{th}$ is observed in the LEC center region.

If the $V_{th}$ scattering in Fig. 3(a) is not caused by the change of the shape of carrier depth profile but the total carrier concentration, the K-value and gamma value must be independent of $V_{th}$. The results of Fig. 5(b) and 6 show that the carrier profile is deeper in the region of clustered dislocations than the other. The change in carrier profile is caused either by the diffusion of Si impurity or the difference in the amount of residual acceptor concentration. Miyazawa et al. reported that the cathodoluminescence intensity was higher in the dislocation network region than the other. Considering both our data and the results in Ref. (3), it is doubtless that the residual acceptor concentration is lower in the region of clustered dislocations.

7. Summary

In this study, by using advanced high density FET array, the microscopic correlations between FET properties and dislocations have been clarified.

The isolated dislocations existing in a LEC doughnut region and in an NO-substrate did not affect FET properties. Only the clustered dislocations such as dislocation networks in the LEC center region and slip lines in the LEC edge region affected FET properties.

In the region of clustered dislocations, the $V_{th}$ is 50-100 mV lower, the K-value is lower and the gamma value is higher. From these results, the residual acceptor concentration is thought to be lower in the region of clustered dislocations than the other regions.

References