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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_{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_{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 fabicate 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_{th}) of MESFET depends on the quality of the semi-insulating substrate.

Several works on the relation between V_{th} and dislocation density have been reported. From the macroscopic V_{th} distribution, M-shaped distribution correspended to the W-shaped distribution of dislocation density has been observed[1]. However, since the macroscopic V_{th} distribution greatly depends on the FET fabrication process[2], it is difficult and incorrect to characterize the substrate quality by the macroscopic V_{th} distribution.

Some discussions of more microscopic V_{th} distribution were reported recently. Miyazawa et al reported that the V_{th} was strongly influenced by the distance between a dislocation and an FET[3]. On the contrary, Winston et al claimed that there was no correlation between the distance and a V_{th}[4]. Takebe et al showed the two-dimentional V_{th} map of large number of FETs with 200μm x 200μm pitch[5]. 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_{th} and clustered dislocations[6].

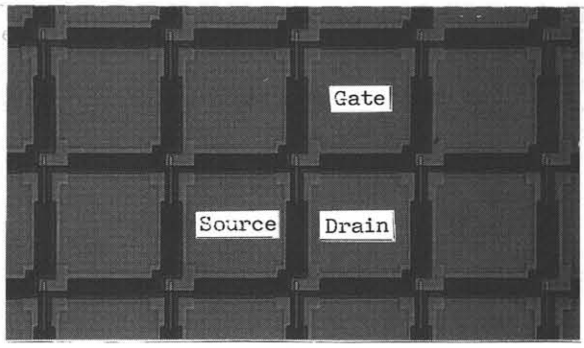


Fig.1 FET array pattern used in this study. FETs are arrayed two-dimentionally by 60μm x 60μm pitch.

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_{th} and dislocations are clearly discussed on the basis of the data of microscopic V_{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

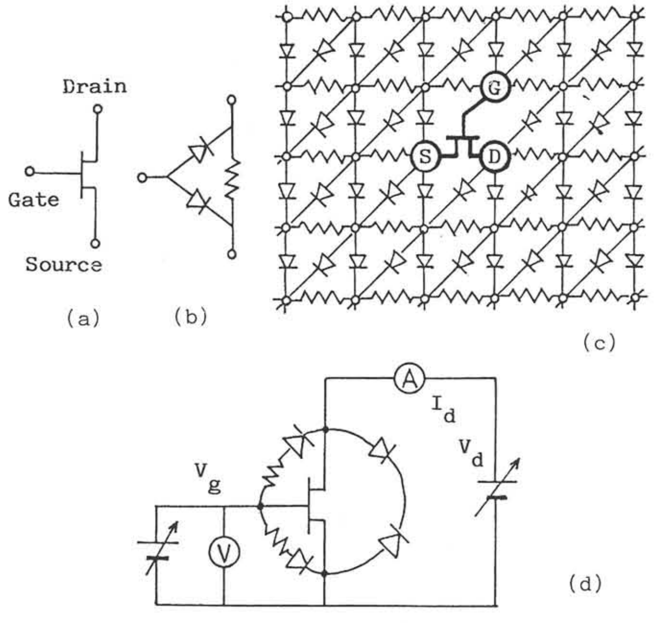


Fig.2 The equivalent circuits of (b) an FET, (c) a two dimensional FET array, and (d) the FET to be measured and surrounding FETs.

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.

Active layer impla.	^{29}Si 60keV 1.2×10^{12} cm^{-2}
n$^+$ layer impla.	^{29}Si 100keV 1.5×10^{13} cm^{-2}
Annealing	Capless in AsH_3 atmosphere 800°C 20 min
Gate metal	W-Al(1at.%) 1000Å
Ohmic metal	AuGe/Ni/Au
Gate length	1.5 μm
Gate width	10 μm
Number of FETs	700

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 MOCVD-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 $(I_d)^{1/2} - V_g$ relation 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

$$\text{Gamma} = |(\Delta V_{th}/\Delta V_d)|.$$

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 dimention 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 2×10^4 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 5×10^3 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.

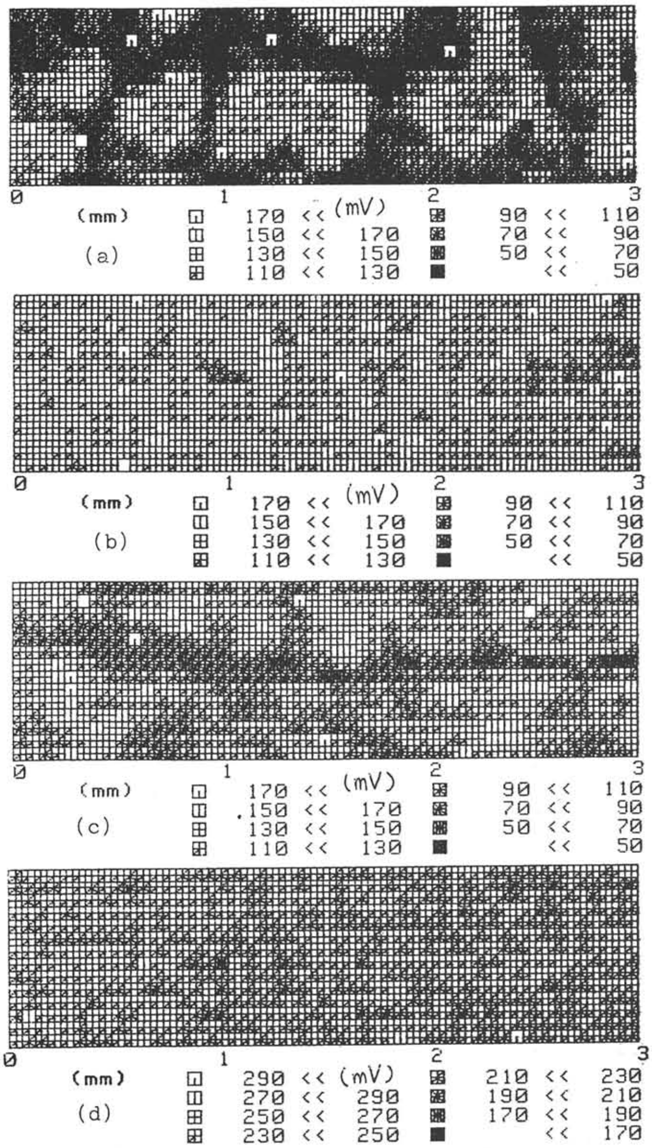


Fig.3 Two dimensional displays of V_{th}. The V_{th} step is 20mV, and in the darker region, V_{th} is lower. (a), (b) and (c) are the central region, the doughnut region and wafer edge region of an undoped LEC substrate. (d) is a central region of an MO-substrate.

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

Substrate and position		Mean value (mV)	Standard deviation (mV)
LEC	Center	+104	34
LEC	Doughnut	+130	14
LEC	Edge	+117	26
MO	Center	+231	11

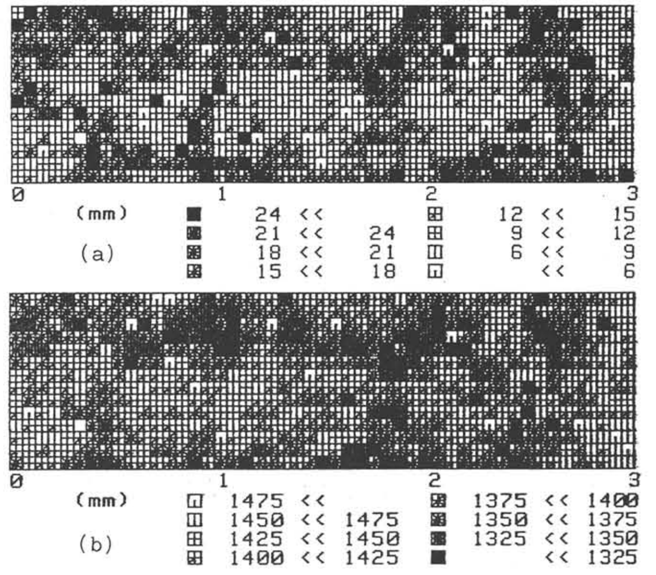


Fig.4 Two dimensional gamma value map (a) and K-value map (b) of the central region of the undoped LEC substrate. The measured region is the same as Fig.3(a).

5. Gamma Value and K-Value Distribution

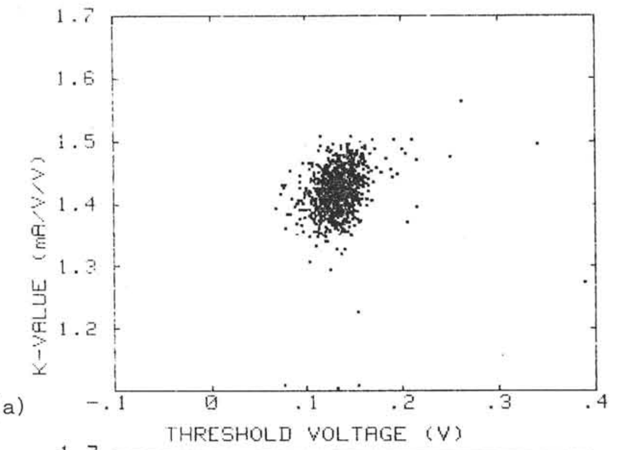
Figure 4 shows the distribution maps of gamma value and K-value in the centeral region of undoped LEC substrate (the same region as Fig.3(a)). Although the contrast is weaker than that of V_{th}, the distinct network patterns can be also observed. In the cell wall region, gamma value is large and K-value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

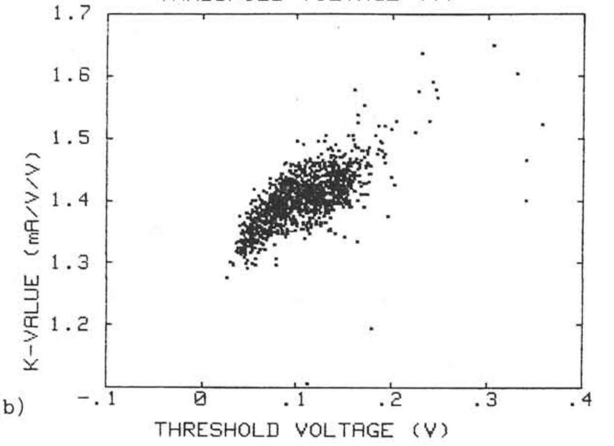
6. Discussion

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 $2x10^4$ 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



(a)



(b)

Fig.5 The correlation between K-value and V_{th}. (a) is the doughnut region of the undoped LEC, and (b) is the central region of the undoped LEC substrate.

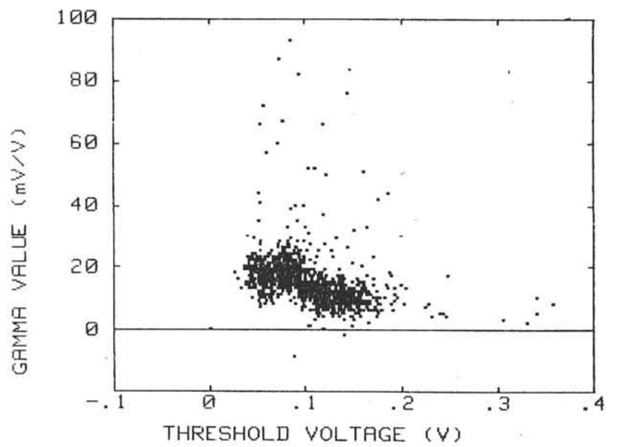


Fig.6 The correlation between gamma value and V_{th} in the cental region of the undoped LEC substrate.

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[3] 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 MO-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.

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