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Uniformity of 3-in., semi-insulating, vertical-gradient-freeze GaAs wafers

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We have evaluated the uniformity in $[\text{EL2}]$, dislocation (or etch-pit) density (EPD), resistivity, mobility, and carrier concentration for 3-in., semi-insulating GaAs wafers grown by the vertical-gradient-freeze (VGF) technique. Although slight W or U patterns were observed in $[\text{EL2}]$ and EPD along the $\langle 110 \rangle$ directions, for the first time, nevertheless the overall uniformity was excellent, and comparable to that in the best In-doped and whole-boule-annealed ingots grown by the liquid-encapsulated Czochralski (LEC) technique. Based on results from implant-activation studies on LEC wafers, it is estimated that the measured nonuniformities in EPD and $[\text{EL2}]$ for the VGF wafers would contribute only about 1% to implant-activation-efficiency nonuniformities in Si-implanted wafers designed for field-effect transistor applications.

The materials-parameter variations found in large (2, 3, and 4 in.), semi-insulating (SI), liquid-encapsulated Czochralski (LEC) wafers have been well correlated with variations of device-parameters, e.g., the pinch-off voltage of a field-effect transistor (FET).^{1,2} In particular, the dislocation density [as measured by etch-pit density (EPD)], deep-donor density $[\text{EL2}]$, resistivity ρ , mobility μ , and carrier concentration n , often exhibit fourfold symmetric patterns, evidently due to the thermal stresses generated during high-temperature crystal growth. Recently, a novel gradient-freeze growth method, employing a vertical tube to produce round ingots, has been successfully used to grow 2- and 3-in. SI GaAs crystals,³ and it is of high interest to know the uniformity of the wafers cut from these ingots. The $[\text{EL2}]$ patterns in the 2-in. VGF material have recently been discussed,⁴ and no fourfold patterns were found. However, in the present report, one of the first on 3-in. material, we do find weak, fourfold $[\text{EL2}]$ and EPD patterns. In spite of this fact, the overall uniformity is excellent.

The wafers discussed in this study were Numbers 78, 79, and 80, from near the tail of a 3-in. SI, vertical-gradient-freeze (VGF) GaAs boule. No discernible differences in the $[\text{EL2}]$ maps were observed for the three wafers. The etch-pit study was performed on No. 78, the electrical measurement investigation on No. 79, and the $[\text{EL2}]$ mapping on No. 80; however, we assume that the properties measured on one wafer were representative of those on the others.

The $[\text{EL2}]$ patterns were measured by means of an automated absorption apparatus, using a wavelength of 1.1 μm , which is strongly absorbed⁵ by neutral EL2 , i.e., EL2^0 . The beam size was about $1 \times 1 \text{ mm}^2$, which allowed about 3500 points to be measured across the surface of the 3-in. wafer. The results are shown in Fig. 1, in the form of a histogram and gray-scale map, produced on a Tektronix Model 4129 graphics-display system. Note that it is difficult to see a discernible pattern in the map itself; however, when 10-mm horizontal $\langle 110 \rangle$ and diagonal $\langle 100 \rangle$ "swaths" are taken

across the wafer, as delineated by the lines superimposed on the map, slight W or U patterns become evident, as seen in Figs. 1(c) and 1(d), respectively. However, the overall $[\text{EL2}]^0$ variation is much less than is typically found in "standard" LEC material, and compares favorably with the best whole-boule-annealed⁶ or In-doped material. The median value of $[\text{EL2}]^0$, about $6 \times 10^{15} \text{ cm}^{-3}$, is significantly lower than that usually found in LEC crystals, evidently because the dislocation density is also lower, as discussed below.

To determine dislocation density, the sample was etched in molten KOH at 450 °C for 40 min. The resulting etch pits, formed at points where dislocations intersect the surface, were manually counted at 75 locations along a $\langle 110 \rangle$ direction, and the data are displayed in Fig. 2. Each dot in Fig. 2

FIG. 1. $[\text{EL2}]^0$ gray-scale map, histogram, and 10-mm horizontal $\langle 110 \rangle$ and diagonal $\langle 100 \rangle$ slices for a 3-in. SI, VGF GaAs wafer.

FIG. 2. Etch-pit density (EPD) along a horizontal $\langle 110 \rangle$ direction for a 3-in., SI, VGF GaAs wafer.

represents the average of counts in three different $400 \times 400 \mu\text{m}^2$ areas around a given location. In spite of this averaging, the scatter is still large, partly because of poor counting statistics. Note that the median etch-pit density (EPD), about 3200 cm^{-2} is like [EL2], much below the median in standard LEC material, and in fact, is comparable to that found in most In-doped material, at least outside the "ring" region.⁷ Note also that the EPD (Fig. 2) seems to track [EL2] [Fig. 1(c)] very well, even reproducing the slight asymmetry on the left-hand side of the wafer. The similarity between EPD and [EL2] patterns is thought to result from the As-rich nature of the regions surrounding dislocations. Since the defect As_{Ga} is an integral part of EL2, we would expect to find more EL2 near dislocations. However, there will always be some EL2, even in dislocation-free regions, as long as the overall stoichiometry is As rich.

The electrical properties, resistivity ρ , mobility μ , and carrier concentration n , along a $\langle 110 \rangle$ direction are shown in Fig. 3. Accurate and reproducible electrical measurements in SI GaAs are inherently difficult, both because of surface conduction and also because of the strong temperature dependence of ρ and n , about 10% per degree K. Thus, the observed variations of ρ , μ , and n in Fig. 3 are probably just due to these effects, rather than to position on the wafer. Again, the electrical uniformity in the VGF wafers is significantly better than that observed in standard LEC material, and is comparable to that found in the best whole-boule-annealed⁶ or In-doped material.

The average values and ranges of the various data are summarized in Table I. The rather low average value of

FIG. 3. Resistivity ρ , mobility μ , and carrier concentration n along a horizontal $\langle 110 \rangle$ direction for a 3-in., SI, VGF GaAs wafer.

[EL2]⁰, about $6 \times 10^{15} \text{ cm}^{-3}$, may cause some concern in regard to the compensation of shallow donors N_D and acceptors N_A . We can estimate $N_A - N_D$ from the relation

$$\begin{aligned} n &\approx \left(\frac{[\text{EL2}]}{N_A - N_D} - 1 \right) \frac{g_0}{g_1} N_C e^{-E_{\text{EL2}}/kT} \\ &\approx 1.8 \times 10^6 \left(\frac{[\text{EL2}]}{N_A - N_D} - 1 \right) \\ &\approx 1.8 \times 10^6 \frac{[\text{EL2}]^0}{N_A - N_D}, \end{aligned} \quad (1)$$

where (g_0/g_1) is a degeneracy factor, taken to equal $1/2$, N_C is the effective conduction band density of states, and E_{EL2} is the EL2 activation energy, taken to be 0.65 eV at 296 K, but somewhat uncertain.⁸ From the values of [EL2]⁰ and n in Table I, we get $N_A - N_D \approx 2.1 \times 10^{15} \text{ cm}^{-3}$. Thus, [EL2]/ $(N_A - N_D) \approx 3.7$, which is a comfortable margin of compensation. In addition, the carbon concentration was measured by the localized-vibrational-mode method to be $1.9 \times 10^{15} \text{ cm}^{-3}$; therefore, it is probable that $N_A \equiv [C]$, and $N_D \ll N_A$. It is theoretically possible that the observed variations in [EL2]⁰ were caused by variations in [C], not [EL2]. However, the close similarity between [EL2]⁰ and the EPD suggests that [EL2] is varying, rather than [C].

The tight distribution of EL2 is highly advantageous from a device point of view. Brierley, Anderson, and Grabinski⁹ have shown that the Si-implant activation percentage, for a metal-semiconductor field-effect transistor (MESFET) application in standard LEC material, varies

TABLE I. Uniformity of a 3-in. VGF wafer along a $\langle 110 \rangle$ direction.

Parameter	No. of data points	Median value (100% of wafer)	range 100% of wafer	Range (80% of wafer)
[EL2] ⁰	69	$5.6 \times 10^{15} \text{ cm}^{-3}$	.4–6.6	5.4–6.1
EPD	75	$3.2 \times 10^3 \text{ cm}^{-2}$	.8–18	0.8–5.0
ρ	11	$2.1 \times 10^8 \Omega \text{ cm}$	.8–2.3	1.8–2.2
μ	11	$6.2 \times 10^3 \text{ cm}^2/\text{V s}$	.0–6.6	6.0–6.4
n	11	$4.8 \times 10^6 \text{ cm}^{-3}$	.1–5.6	4.6–5.6

with EL2 concentration, about 1% per $1 \times 10^{15} \text{ cm}^{-3}$ change in [EL2]. If these numbers can be applied to our VGF wafers, then a variation in implant activation of only 1% would be expected, *from this cause*, across the wafer. Of course, an independent study of the same type will have to be carried out for the VGF material, but it is expected that the same physical mechanisms are applicable.

The dislocation (or EPD) distribution does not appear to be nearly as tight as that of [EL2], according to the range listed in Table I. However, much of this variation is evidently due to poor counting statistics, because of the low EPD. Also, because the average EPD is low, very few devices on such a wafer would have dislocations within $30 \mu\text{m}$ or so, beyond which the dislocation proximity effect is quite weak.¹⁰ Thus, it is doubtful that the concentration of dislocations observed in this wafer would have a strongly deleterious effect on devices. It should also be emphasized that the low dislocation density in the VGF method is achieved without isoelectronic doping which is known to produce substrate-epi lattice mismatch and poor thermal conductivity.

Finally, a comparison of these results with those of a recent study on 2-in. VGF material is useful.⁴ Although the absolute [EL2] values are about the same in the 2- and 3-in. wafers, the variations in [EL2], and also those in ρ and μ , are smaller for the larger VGF wafers, which is somewhat surprising. At a minimum, it suggests that the transition from 2- to 3-in. crystal growth has been successfully accomplished. Also, we did not observe the strong asymmetry in [EL2] found in some of the 2-in. wafers,⁴ although both [EL2] and the EPD in our 3-in. wafers were higher in a small region near the left edge than along the right edge.

In summary, the vertical-gradient-freeze crystal-growth method appears to be capable of producing 3-in.,

semi-insulating GaAs wafers with low dislocation density, and high uniformity in [EL2], ρ , μ , and n . No strong asymmetries in these quantities were found, although [EL2] and EPD exhibited slight, but discernible, W or U patterns.

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