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High-resolution resistivity mapping of bulk semi-insulating GaAs by point-contact technique

W. Siegel [a], G. Kühnel [a,*], C. Reichel [a], M. Jurisch [b], B. Hoffmann [b]

[a] *Institut für Experimentelle Physik, TU Bergakademie Freiberg, D-09596 Freiberg, Germany*
[b] *Freiberger Compound Materials GmbH, D-9584 Freiberg, Germany*

Abstract

Electrical non-uniformities connected wih the cellular structure of dislocations have been investigated by high-resolution point-contact measurements both in liquid encapsulated Czochralski (LEC)-grown and in vertical gradient freeze (VGF)-grown GaAs. Comparing maps of point-contact current with those of the photoluminescence intensity, in most cases good agreement was observed. The reason for this correlation with regard to relevant defect levels is discussed. Improvements in the homogeneity of semi-insulating GaAs wafers by different ingot-annealing processes are clearly proved by the point-contact technique. © 1997 Elsevier Science S.A.

Keywords: Gallium arsenide; Semi-insulating; Homogeneity; Resistivity

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1. Introduction

Parameters of GaAs IC devices (especially the threshold voltage of the field effect transistors (FETs)) are impaired by mesoscopic electrical non-uniformities of the semi-insulating (SI) substrates [1]. Hitherto, mainly optical methods, such as near-band gap photoluminescence (NBG PL) and infrared absorption of EL2, have been used to detect non-uniformities connected with the cellular structure of dislocations. However, optical methods do not necessarily reflect electrical properties.

A point-contact technique [2]—similar to the spreading-resistance method for Si—has only been used in recent times for the high-resolution profiling of GaAs, especially of low-resistivity GaAs. Different authors [3,4] showed that in a modified form such a technique is also suitable for semi-insulating (and medium-resistivity) GaAs.

In this paper the performance of the point-contact method for the high-resolution resistivity mapping of SI GaAs grown by the liquid encapsulated Czochralski (LEC) or vertical gradient freeze (VGF) technique is shown. The efficiency of different annealing procedures for the improvement of the homogeneity of SI GaAs wafers especially can be checked by this method. For comparison NBG PL intensity mapping was performed on the same samples.

2. Experimental details

Undoped 100 mm LEC-grown SI GaAs substrates (dislocation density $5-10 \times 10^4$ cm^{-2}) taken from regular wafer production by FREIBERGER as well as 40 mm undoped SI GaAs wafers (average dislocation density 10^3 cm^{-2}) grown in the laboratory using the VGF technique [5] were investigated.

A tungsten carbide tip with a radius of about 20 μm was moved in steps of 25–50 μm over the polished sample surface. A forward bias of 1 V was applied for all measurements of the point-contact current I_{PC}. Further experimental details are given in [6].

Calibration using some samples with a different resistivity ρ yielded results indicating that the point-contact resistance R_{PC} ($= U/I_{PC}$) is nearly proportional to $\rho^{0.7}$ over the resistivity range of interest (10^6-10^8 Ω cm).

A Scantek system with 5 mW HeNe laser excitation (632 nm) and Si detector (spatial resolution 20 μm) was used to map the NBG PL at room temperature.

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* Corresponding author.

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3. Results

Topographs of the point-contact current I_{PC} reflect clearly the cellular structure of dislocations as revealed by comparison with the etch-pit pattern of the same area. In the case of LEC GaAs (Fig. 1) the cell interiors appear as holes or valleys of low I_{PC} (high resistivity) surrounded by cell wall regions of high I_{PC} (lower resitivity). Between cell walls and cell centers differences of I_{PC} by a factor of up to 6 occur. The average cell diameter is about 500 μm, correlating to the high dislocation density.

Compared with this, in the case of VGF GaAs (Fig. 2) peaks of I_{PC} in flat surroundings are arranged in the form of a cell wall but interrupted. The corresponding cell diameter is about 2.5 mm.

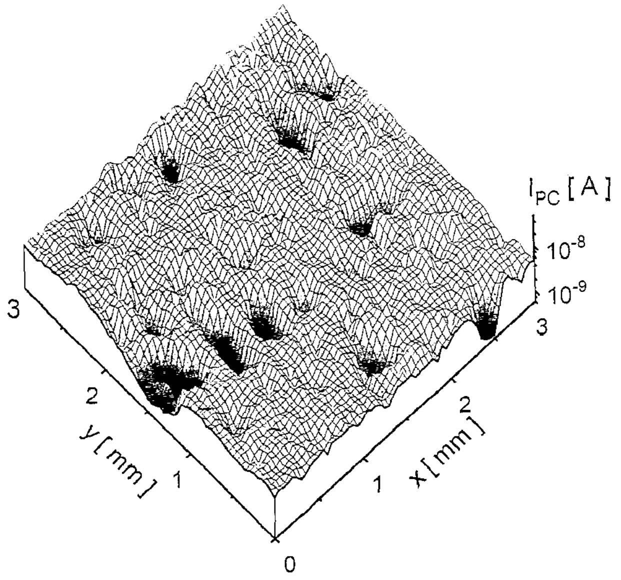

Fig. 1. Topograph of I_{PC} from a semi-insulating LEC GaAs wafer ingot-annealed by a single-step process.

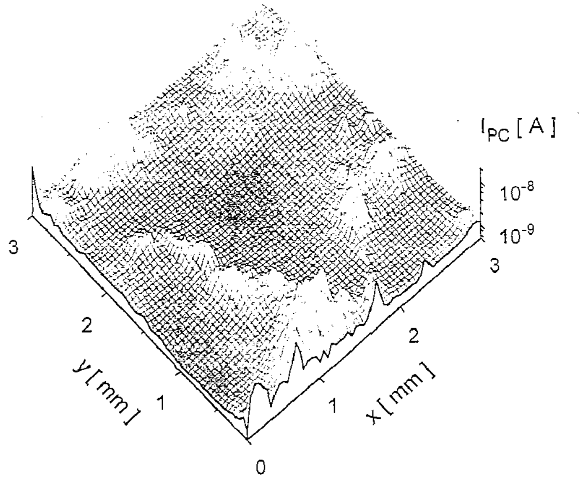

Fig. 2. Topograph of I_{PC} from a semi-insulating as-grown VGF GaAs sample.

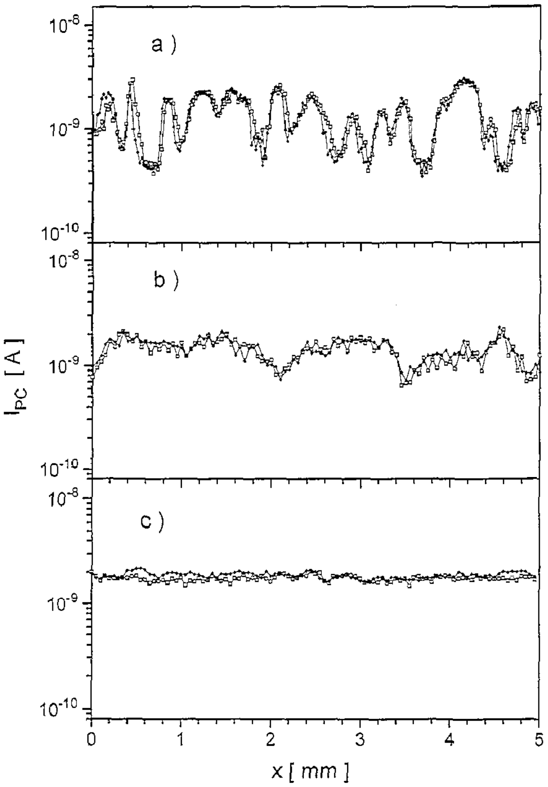

Fig. 3. Line scans of I_{PC} from LEC GaAs wafers (a) as-grown, (b) after single-step ingot annealing, (c) after multiple-step ingot annealing.

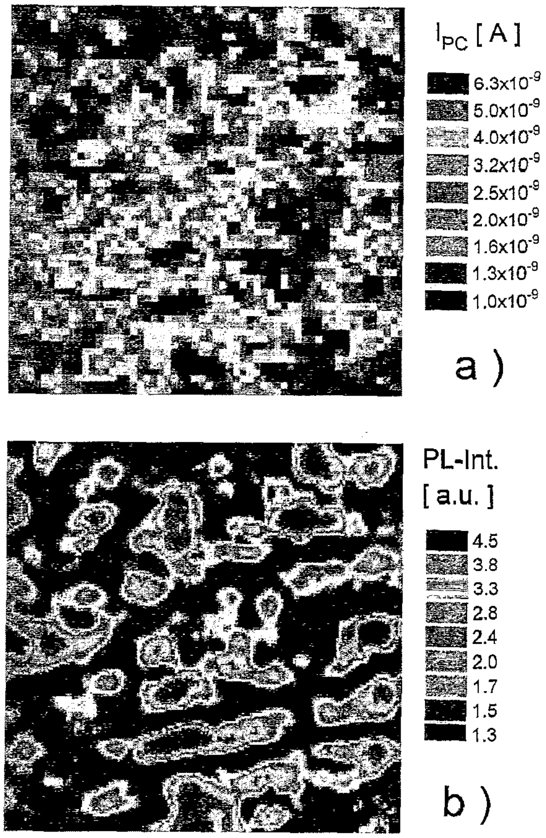

Fig. 4. Topographs of (a) I_{PC} (step width 50 μm) and (b) NBG PL (step width 20 μm) from identical areas (3 × 3 mm²) of a LEC GaAs wafer after single-step annealing.

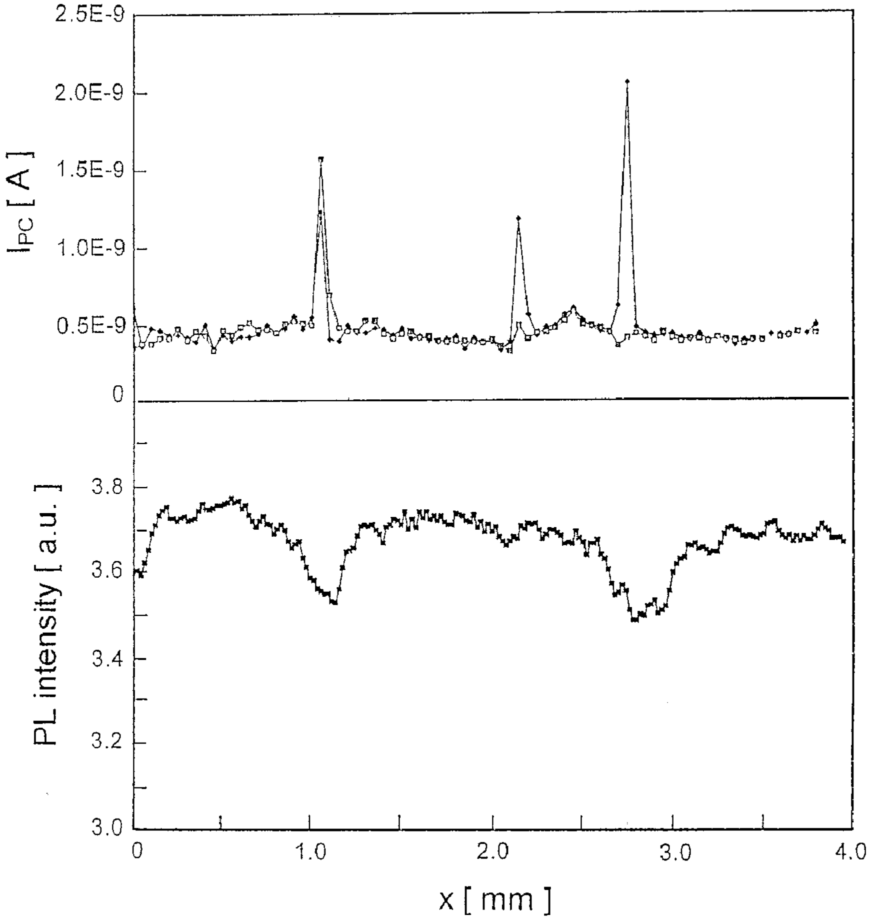

Fig. 5. Line scans of (a) I_{PC} (line distance 50 μm) and (b) NBG PL from an as-grown VGF GaAs sample.

By post-growth ingot annealing homogenization of the resistivity in LEC GaAs can be achieved, clearly proved by I_{PC} maps and profiles, respectively. In Fig. 3 two parallel line scans of I_{PC} are shown for each one of the samples prepared from crystals (a) in as-grown state, (b) after single-step ingot annealing and (c) after multiple-step ingot annealing. From Fig. 3 it is clearly obvious that only multiple-step annealing yields satisfactory homogenization. The uniformity of resistivity in the samples increasing from (a)–(c) correlates to a clear enhancement of the Hall mobility. For nearly all LEC samples investigated (both as-grown and ingot-annealed) a strong correlation of the topographs of the NBG PL intensity to those of I_{PC} exists. This is shown in Fig. 4 for an identical 3×3 mm^2 area of a wafer ingot-annealed by a single-step process. Cell walls correspond to high PL intensities and cell interiors to low ones. However, in the case of VGF GaAs a different behavior was observed. Although the cellular structure in the PL topograph was hard to recognize (cell interior/wall contrast of only some percent) cell walls appear as regions of lower PL intensity. Therefore, the PL profile is inverse to the I_{PC} profile (Fig. 5). Also an LEC GaAs sample quenched at a high cooling rate shows distinctly different maps of I_{PC} and PL (Fig. 6). In contrast to Fig. 4 cell walls appear as dark lines of lower current and the cell interiors as regions of higher current in the I_{PC} maps. Moreover, in the cell center a lowering of I_{PC} is observed.

4. Discussion

The observed differences of the I_{PC} values between cell walls and cell centers correspond via calibration to a resistivity variation up to one order of magnitude. According to [7] these differences are mainly due to accumulation of the EL2 center (the antisite defect As_{Ga}) in the dislocation-rich cell walls. However, concentration variations of other defects (donors shallower than the EL2 and/or acceptors) can also contribute to the resistivity difference between walls and centers.

The double line scans in Fig. 3 demonstrate the excellent reproducibility of the point-contact technique used. Moreover, from Fig. 3 it is obvious that the homogenization of the resistivity by annealing occurs in the following way for LEC GaAs: first, most narrow holes (minima of I_{PC}) disappear (single-step annealing)

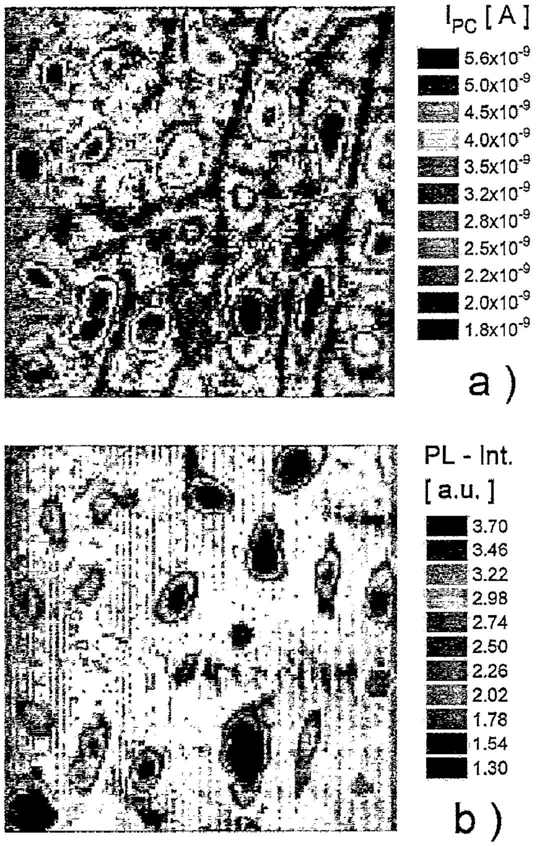

Fig. 6. Topographs of (a) of I_{PC} (step width 25 μm) and (b) NBG PL (step width 25 μm) from identical areas (3×3 mm^2)of an LEC GaAs sample quenched at a high cooling rate.

and then a further reduction of the remaining wide holes takes place. These steps of homogenization can also be followed up by PL mapping and IR profiling.

The good agreement of the topographs of NBG PL intensity and of the point-contact current in the case of as-grown and of ingot-annealed semi-insulating LEC GaAs samples justifies the usual application of PL mapping for homogeneity checking in the wafer production. However, this close correlation is surprising because in SI GaAs different defects are responsible for the resistivity and for the NBG PL intensity. The latter is determined by lifetime-limiting recombination centers [7] which are not identical with the EL2 (governing the electrical properties of SI GaAs). From the agreement of the topographs of the PL intensity and of I_{PC} it can be concluded that a spatial anticorrelation of the recombination centers to the EL2 must exist. Indeed, for EL6 (one of the medium deep donors mostly present in undoped GaAs) such an anticorrelation was detected by the corresponding photoluminescence band at 0.8 eV [8]. Therefore, the EL6 defect (suggested to consist of $As_{Ga}-V_{As}$ [9]) is a promising candidate for the recombination center in question.

The fact that different defect centers are responsible for the point-contact current and for the NBG PL intensity is confirmed by the observations in Figs. 5 and 6. In these cases the PL intensity profiles and maps do not correlate to the I_{PC}. The anticorrelation of I_{PC} and of the PL intensity observed on VGF GaAs (Fig. 5) can be attributed to the spatial correlation of the defects EL2 and EL6, assumed to be responsible for I_{PC} and PL, respectively.

The applicability of the point-contact technique to other high-resistivity semiconductors is to be expected and will be studied in the future. In the case of SI InP this check was already successful [6].

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