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Synchrotron X-ray topography and electrical characterization of epitaxial GaAs p–i–n structures

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Abstract

Results from synchrotron X-ray topography and electrical characterization of thick epitaxial GaAs p–i–n structures suitable for manufacturing of radiation detectors are reported. The structures under study have been grown with hydride vapor phase epitaxy method. A comprehensive set of large-area transmission, large-area back-reflection and transmission section topographs are analyzed. The X-ray topography results are compared with the dark current density of the detector diodes. The X-ray topographs show the defect structure in the samples and provide important information for epitaxial process optimization.

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Keywords: X-ray topography; Epitaxial GaAs; P–i–n diode

1. Introduction

GaAs is a widely studied material for detector applications. High-purity epitaxial GaAs is one of the most promising alternatives to silicon for room temperature spectroscopic radiation detectors [1]. The epitaxial material characterized in this work yields radiation detectors with good performance. A typical energy resolution for monolithic pad type p–i–n detector manufactured is 200–250 eV at 5.9-keV primary energy. Charge collection efficiencies of nearly 100% have been measured.

GaAs theoretically provides a very small dark current density due to the relatively wide band gap. However, achieving low leakage current levels necessary for a high-resolution energy dispersive operation sets strict demands for the material quality.

The aim of this work is to study the defect structure of the epitaxial layers by means of synchrotron X-ray topography [2,3] and to compare the results with the electrical properties of the detector diodes.

2. Growth process and experimental

The epitaxial p–i–n structures were grown by hydride vapor phase epitaxy (HVPE) on a commercial 2″ n-type GaAs (1 0 0) substrate with 4° miscut towards ⟨1 1 1⟩ at A.F. Ioffe Physico-Technical Institute, St. Petersburg. The thickness range of high purity i(n)-layers studied in this work is 100–400 μm. The thickness of the p-layer on the i(n)-layer is approximately 2 μm.

Synchrotron X-ray topography imaging in back-reflection and transmission geometries has been applied in order to gain information on the crystal defects of the epitaxial GaAs wafers. The synchrotron topography was done at HASYLAB-DESY F1 topography station using the continuous spectrum of radiation from the DORIS storage ring bending magnet source. The large-area transmission and large-area back-reflection topographs were made on high-resolution VRP-M films from Slavich. Subsequently

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they were magnified with an optical microscope equipped with a digital camera.

Mesa type pad detectors for the electrical characterization were manufactured at Micronova, Helsinki University of Technology. The mesa etching was conducted with an inductively coupled plasma reactive ion etcher (ICP-RIE) system utilizing $SiCl_4$ as the reactive gas. PECVD dielectric was deposited on the mesa structure to passivate the diodes and to provide protection against surface contamination. Fig. 1 shows a photograph of the sample studied in this work. A set of complete particle detector diodes can be seen in this piece of epitaxial GaAs wafer.

3. Results and discussion

Synchrotron X-ray topographs made in the back-reflection geometry typically probe the surface of the sample. The X-ray energy of the 004 diffraction images seen in Figs. 2(a) and (b) is 4.4 keV, which gives an attenuation depth of about 5 μm in GaAs. The most critical part of the detector diode is the p–i(n) interface and thus the back-reflection topography method is especially suitable for the characterization of epitaxial detector structures.

Fig. 2(a) shows a 004 X-ray topograph of a region of the sample with a high dark current density of 4200 nA cm^{-2} and Fig. 2(b) shows a region of the same sample with a low dark current density of 1.2 nA cm^{-2}. Misfit dislocation images in horizontal and vertical directions and images of threading dislocations can be seen in the Figs. 2(a) and (b). The horizontal dislocation images in Figs. 2(a) and (b) are parallel and the vertical dislocation images are perpendicular to the projection of miscut direction. The dislocation densities are listed in Table 1. The values in Table 1 are calculated from $1 \times 2.4\text{-mm}^2$ back-reflection topographs, out of which smaller segments are shown in Figs. 2(a) and (b). The difference in the leakage current rate is several orders of magnitude larger than the difference in the threading and horizontal misfit dislocation densities. Thus it is likely that the vertical misfit dislocations, which are perpendicular to the projection of miscut direction, are of most detrimental type and are the ones providing a low potential route for leakage current across the p–i(n) interface.

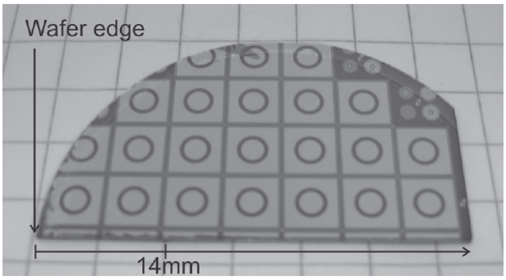

Fig. 1. Photograph of a set of complete particle detector diodes manufactured on a 2″ wafer. The grid in the underlying paper is 7 mm.

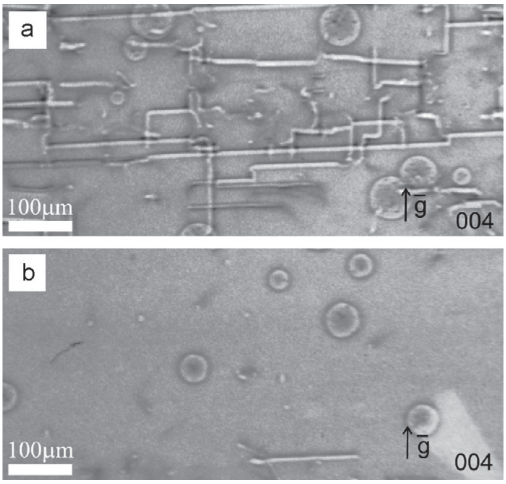

Fig. 2. 004 back-reflection topographs of the p-side of the epitaxial layers. (a) corresponds to area with high dark current and (b) to low dark current.

Table 1
Dislocation densities at high leakage current and low leakage current areas of Fig. 2, denoted as areas (a) and (b), respectively

	Area (a)	Area (b)
Leakage current density (nA cm^{-2})	4200	1.2
Threading dislocations (cm^{-2})	14,000	7000
Horizontal misfit dislocations (cm^{-2})	15,000	850
Vertical misfit dislocations (cm^{-2})	7100	0

The circular spots, which can be seen in Figs. 2(a) and (b), may be due to precipitates in the p-layer or in the topmost part of the i-layer. Similar spots can also be seen in optical micrographs of the epitaxial surface. However, no correlation between the density of the spots and electrical properties was found.

Fig. 3 shows the dark current of a p–i–n diode as a function of the distance from the wafer edge and six 004 back-reflection topographs of areas located at the positions marked in the figure. The correlation of the dark current density to the dislocation density is very strong and appears to be exponential rather than linear.

Transmission topographs show the dislocation structure throughout the whole sample. Fig. 4 shows a 400 transmission topograph of the high dark current area of the same sample as the back-reflection topograph of Fig. 3. The result is consistent with the back-reflection topograph of Fig. 3 because the misfit dislocation network on the p-side is readily visible. The dislocation densities of the samples with inferior electrical quality are very large,

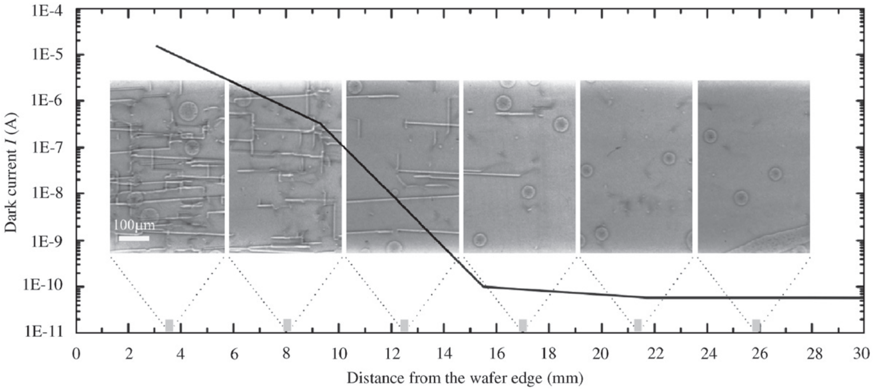

Fig. 3. 004 back-reflection topographs showing the correlation between dark current and dislocation densities in an approximately 135-μm thick high-purity HVPE-GaAs layer.

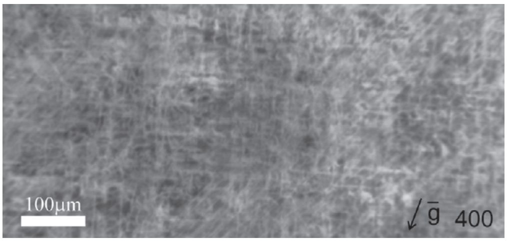

Fig. 4. 400 transmission topograph of a region of the sample with a high density of dislocations in the epitaxial layer.

estimated from the image to be $\geqslant 10{,}000\,\text{cm}^{-2}$ because no individual dislocations can be distinguished.

Figs. 5(a) and (b) show transmission topograph images of a detector structure with a low dark current density of $1.2\,\text{nA}\,\text{cm}^{-2}$. Compared to Fig. 4(a) a small dislocation density is observed and even individual dislocation lines can be distinguished. The straight parallel and slightly blurred lines are evidently images of misfit dislocations at the substrate–epilayer interface. A similar dislocation network was also observed in an earlier study [4]. The dislocations seen in Figs. 5(a) and (b) are most likely of mixed type. No pure screw dislocations using the Burgers vector analysis could be found. The sharp lines seen in the figure are images of dislocations located near the surface of the sample.

The dots in the transmission images are interpreted as precipitates according to the dynamical theory of diffraction [5]. Similar precipitates have also been observed in MOCVD-grown GaAs layers on germanium substrate [6]. No correlation of these dots and electrical properties was found. The dislocation type that corresponds to high leakage current density could not be unambiguously determined using Burgers vector analysis. Further studies are needed to address more exactly the effect of certain dislocation type to electrical properties. More precise information could be obtained by first etching, for example, $500 \times 500\text{-}\mu\text{m}^2$ mesa diodes on the sample. The etched mesa would be clearly seen in the topograph and thus the electrical properties and the synchrotron X-ray topographs of a carefully selected diode could be compared.

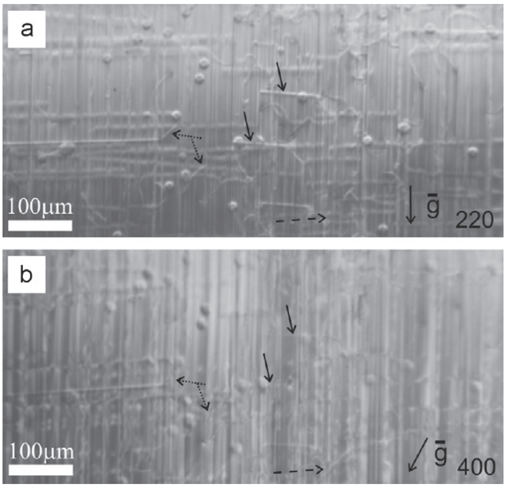

Fig. 5. (a) 220 and (b) 400 transmission topographs showing the dislocation structure in the sample. The arrows are pointing out dislocation images, which disappear in either of the topographs.

4. Conclusions

The results show that wafer uniformity and crystal quality play a significant role when epitaxial high purity material is used for manufacturing detector diodes. The epitaxial layers contain a low concentration of defects, which is required for the manufacturing of high-quality detectors. The uniformity issue is highlighted when detector components having large area are manufactured. It is also shown that synchrotron X-ray topography provides valuable information for the process development.

Acknowledgment

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