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New Characterization Technique for Detection of Atomic-sized Crystalline Defects and Strain Using Moiré Method

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Abstract

Recently we have developed an optical sampling Moiré technique to visually and quantitatively determine the tiny defect locations. We applied this technique for GaN HEMT devices, and successfully detected distribution of strain as well as tiny defects in AlGaN/GaN crystalline structure.

1. Introduction

Defect detection technique is essential for manufacturing semiconductor devices. However, crystalline defects are too tiny to detect with high accuracy. Conventional detection method which is visual observation and counting by a cross-sectional transmission electron microscope (TEM) is lack of accuracy and time-consuming. Wang et al. [1] proposed a Fourier transform (FT) filtered sampling Moiré technique to detect defects in crystal structures by realizing defect visualization of tiny defects in a large view field, high-accuracy detection, fast automatic processing in an arbitrary direction and low cost at the same time. In Fig. 1 [1], a GaN/AlGaN crystalline structure is separated to several gratings in their principal directions by 2D FT. Using 2D fast FT (FFT) filter, the grating images in the x and y directions were obtained. After a sampling pitch was determined, the sampling Moiré fringes were generated and the Moiré phases in the x and y directions were calculated.

In this paper, we firstly report atomic-sized defects and strain detection with AlGaN/GaN crystalline structure in a high electron mobility transistor (HEMT) device using this Moiré method.

2. Sample structures and Moiré phase calculation

Samples

Three blanket and two pattered AlGaN/GaN structures were prepared for TEM observation and defects and strain detection using the Moiré method. In case of blanket samples, a 30 nm-thick AlGaN layer were epitaxially grown on GaN/Si-sub followed by reactive ion etch (RIE) and/or wet treatment. The wet treatment is effective for removal of plasma-damaged layer [2]. In case of patterned structure, a 30 nm-thick AlGaN layer on GaN/Si-sub was recessed by RIE. One recessed sample was annealed in NH_3 ambient to recover rough surface after RIE [3]. For all samples, TEM images with high resolution (e.g. 4000 pixels x 6000 pixels) were obtained.

Moiré phase calculation

The grating images in the x (horizontal) and y (vertical) directions were obtained using 2D FFT. The defects can be visually observed from Moiré fringes (defects mean discontinuous portions in a Moiré phase). The number of defects was counted by specific software. In addition, strain ε is calculated by the following equation;

$$\varepsilon = (p-p_0)/p_0$$

where p_0 is a standard grid pitch (10.6 pixels in x direction, 19.7 pixels in y direction), and p is an actual grid pitch in the each observed area. Averaging filter processes within 33x33 pixels in x direction and 59x59 pixels in y direction were respectively applied to obtain strain maps.

3. Results and discussion

The original TEM image of as epitaxially grown AlGaN/GaN structure is shown in Fig. 2(a). The Moiré phase images in x and y direction, and distribution of dislocations are shown in Figs 2(b), 2(c), and 2(d), respectively. The location of dislocations is clearly detected from Moiré phases. Fig. 3 shows the dislocation distributions of samples after RIE and after wet treatment. With 'after RIE' sample (Fig. 3(a)), an amorphous layer was observed at the AlGaN surface, which is thought to be an oxidized layer [2], and numbers of defects were observed at the amorphous/AlGaN interface. However, after wet treatment (Fig. 3(b)), amorphous layer was removed, resulting in drastic decrease of defects at the interface.

Strain maps of as epi AlGaN/GaN structure are shown in Fig. 4. Both in x and y direction, at maximum 0.10 or more strain was detected. Although some highly strained points were agreed with dislocation position, others were located regardless of dislocation. Thus, it is revealed that highly strained AlGaN and GaN crystals exist without making dislocation.

Fig. 5 shows the dislocation maps of recessed AlGaN/GaN structures. Before thermal annealing (as RIE), many dislocations exist in the bulk crystal as well as the recessed surface (Fig. 5(a)). These dislocations slightly decreased after annealing (Fig. 5(b)). The numbers of dislocation and the dislocation density were summarized in Table I.

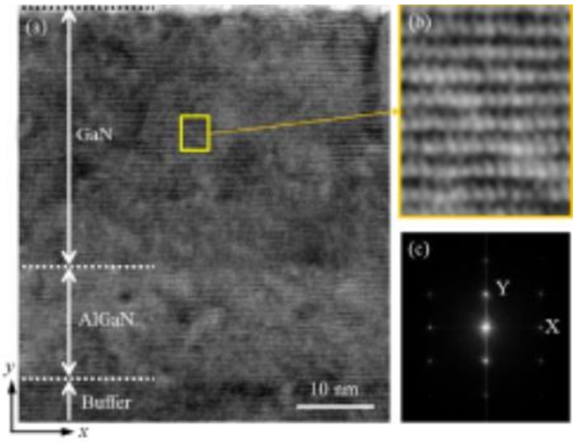

Fig. 1 (a) TEM image of AlGaN/GaN structure. (b)Enlarged view. (c) Frequency spectrum after 2D FET. [1]

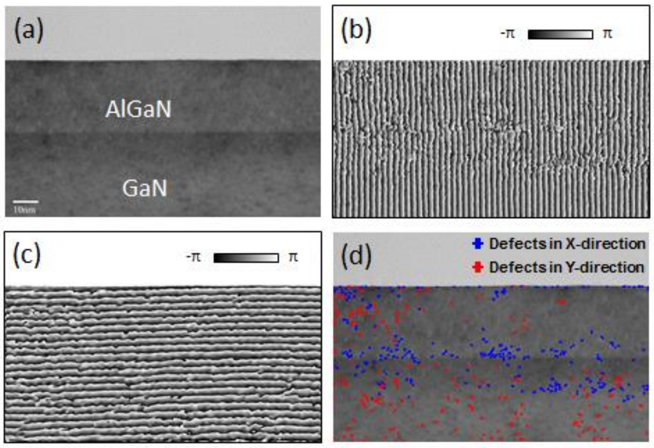

Fig. 2 TEM image, Moiré phase and defect distribution of as epi AlGaN/GaN structure. (a) Original TEM image of as epi AlGaN/GaN structure. (b) Moiré phase in x direction. (c) Moiré phase in y direction. (d) Distribution of dislocation.

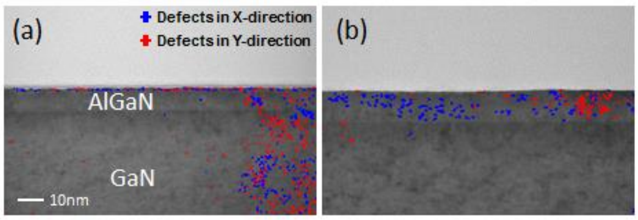

Fig. 3 Dislocation distribution in AlGaN/GaN structure. (a) After RIE. (b) After wet treatment.

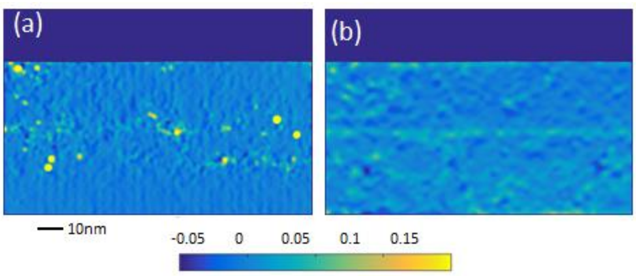

Fig. 4. Strain maps of as epi AlGaN/GaN structure. (a) x-direction. (b) y-direction. (In the color bar, 0.15 is at the rightmost side)

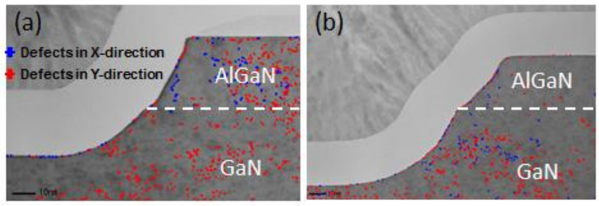

Fig. 5. Defect distribution in recessed AlGaN/GaN structure. (a) Before thermal annealing (as recessed). (b) After thermal annealing.

Table I Dislocation counts and density.
(Sum of x direction and y direction)

	Number of dislocation		Dislocation density (counts/1E6 pixel^2)	
	Surface	Bulk	Surface	Bulk
As epi	73	793	260	72.5
After RIE	268	1185	712	70.9
After wet treatment	30	453	107	52.2
Before annealing	89	658	255	89.7
After annealing	102	647	235	62.6

4. Conclusions

We applied the optical sampling Moiré technique for defect detection with GaN HEMT devices. Atomic-sized dislocations in AlGaN/GaN crystalline structure were clearly detected with nm-scale spatial resolution. Since the distributions and the number of dislocation depend on the process conditions, we confirmed that this technique is quite useful for device development. Moreover, strain in AlGaN/GaN crystal was successfully calculated with nm-scale resolution. We also confirmed that this sampling Moiré technique is applicable to silicon devices.

References

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