Direct observation of carrier distribution in laser diode using off-axis electron holography and Lorentz microscopy

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Abstract. The carrier distribution of a buried laser diode structure was examined using off-axis electron holography and Lorentz microscopy, and a two-dimensional structure of p-n junctions was clearly observed. The sensitivity of off-axis electron holography and Lorentz microscopy to different carrier concentrations of GaAs specimen was compared.

1. Introduction

The measurement of carrier distributions in semiconductor devices is very important in the development of new devices and for the analysis of device failure. The application of off-axis electron holography in the silicon semiconductor industry has attracted considerable attention in recent years [1-3]. The first Lorentz microscopy observation of Si p-n junction was carried out by Merli et al. [4-6]. Twitchett et al. quantitatively examined the Si p-n junction using both off-axis electron holography and Lorentz microscopy [7]. We have been concerned with compound semiconductors such as GaAs [8] in observation using off-axis electron holography, and found that the process of removing the damaged layer formed by a focused ion beam (FIB) is unavoidable [9,10] when the TEM specimen is fabricated using a FIB.

We compared the sensitivity of off-axis electron holography and Lorentz microscopy to different carrier concentrations in a GaAs specimen. In addition, a two-dimensional carrier distribution of a buried laser diode structure was observed using these methods.

2. Experimental Details

2.1. GaAs test sample with step-like carrier concentration

We examined p-n thin films grown on a GaAs substrate by metal-organic chemical vapour deposition (MOCVD). The structure of the TEM specimen is shown in Fig. 1. Silicon and zinc were used as n-type and p-type dopants, and the composition of the samples was for testing the sensitivity of electron holography and Lorentz microscopy to different carrier concentrations.

The specimen was prepared using a SHINT SMI3050TB (Triple Beam) FIB system, which combines a Ga ion beam, a scanning electron microscope for process monitoring, and an Ar ion beam to remove the FIB damaged layers [11]. The detailed procedure for preparing TEM specimens was reported in ref. [10]. The specimen suitable for TEM observation was thinned to 300 nm in the FIB.
system. Finally, the FIB damaged layer was removed by milling the sample surface for 5 minutes with a 1.0-kV Ar ion beam in the FIB system.

Electron holographic and Lorentz microscopy observations were made with a JEOL-3100F TEM operating at 300 kV, and equipped with a Schottky field-emission electron gun and an electron biprism. Digital holograms with $1024 \times 1024$ pixels were recorded using a slow-scan charge-coupled device (CCD) camera system. We used 13 holograms with different initial phases for phase reconstruction. Digital holograms with $4096 \times 4096$ holograms were recorded using a slow-scan CCD camera system. The hologram was an electron biprism was used for the electron holography and Lorentz microscopy experiment. Digital 4096 × 4096 holograms were recorded using a slow-scan CCD camera system. The hologram was reconstructed using a conventional Fourier transform method.

2.2. Semiconductor Laser Diode

An InP-based buried laser diode structure was produced by using MOCVD and etching process. The FIB system was used to thin down a TEM specimen to 300 nm. Surfaces of the specimen were milled for 15 minutes using an Ar ion beam at an accelerating voltage of 1.0 kV at liquid N$_2$ cooling temperature and an incident angle of 10°.

A Hitachi HF-3300 TEM operated at 300 kV equipped with a cold field-emission electron gun and an electron biprism was used for the electron holography and Lorentz microscopy experiment. Digital holograms were recorded using a slow-scan CCD camera system. The hologram was reconstructed using a conventional Fourier transform method.

3. Results and Discussions

3.1. GaAs with step-like carrier concentration

The reconstructed phase image is shown in Fig. 1(a). The p- and n-type regions are clearly seen as areas of dark and bright contrast, and some differences of changing dopant concentrations can also be seen. The interface between the $1 \times 10^{19}$ cm$^{-3}$ region and $1 \times 10^{18}$ cm$^{-3}$ regions is clearly seen in the p-type area, and the $1 \times 10^{17}$ cm$^{-3}$ and $1 \times 10^{16}$ cm$^{-3}$ regions can be distinguished. A detailed analysis of the phase image has been presented in ref. [10].

The defocus images are shown in Fig. 1(b)-(g). The p-n junctions were clearly seen at both 0.6 mm and 1.0 mm. Some differences of changing dopant concentrations can also be seen. A detailed analysis of the phase image has been presented in ref. [10].

![Figure 1](image-url)

**Figure 1.** Observation of GaAs with step-like carrier concentration: a) phase image b-g) defocus images.
under-focus and over-focus, but interfaces of different carrier concentration are hardly observed in each image. In the 1.4 and 2.9 mm defocus images, the interface between $1 \times 10^{19}$ cm$^{-3}$ and $1 \times 10^{18}$ cm$^{-3}$ regions in the p-type area are slightly seen. Compared with the phase image of the off-axis electron holography, the defocus image of Lorentz microscopy has lower sensitivity to different dopant concentrations.

From a practical point of view, Lorentz microscopy is not useful in the detection of differences of only one order of magnitude in carrier concentrations. However, if the location of an abrupt p-n junction needs to be checked, Lorentz microscopy is very practical because it does not requires an electron biprism and is an easier measurement to carry out than off-axis electron holography. In addition, the vacuum region which a reference wave comes through is unnecessary. For observations using off-axis electron holography, the vacuum region has to be made close to the region of interest, so preparing a TEM sample for a semiconductor device can be very difficult.

### 3.2. Semiconductor Laser Diode

To evaluate how well commercial devices perform, they need to be evaluated using Lorentz microscopy and off-axis electron holography. We used these methods to observe a buried laser diode structure. An in-focus image of a laser diode is shown in Fig. 2(a), where only the active layer is observable. A defocus image at -6.7 mm under-focus is shown in Fig. 2(b). The two-dimensional structure is clearly seen by black and white double contour lines. A defocus image at +6.7 mm over-focus is shown in Fig. 2(c). At double contour lines, black and white lines are inverted from the under-focus image. Since these inverted black and white lines appear in both images, these lines indicate p-n junctions.

A reconstructed phase image of the laser diode device which had poor operating characteristics is shown in Fig. 3(a). In this hologram, the interference region and spacings between the interference fringes are 5 µm and 30 nm. The p-n junction of the laser device can be also clearly seen. As discussed previously, a significant advantage of off-axis electron holography is its high sensitivity. The highly n+ doped area, which cannot be observed in defocus images, is visible in the phase image. Figure 3(b) shows an enlarged phase image from the dashed frame in Fig. 3(a). The interference region and spacings between the interference fringes are 1.5 µm and 5 nm at this hologram condition. The phase image shows clear fine structure of the laser device. The designed location of the p-n junction was the dashed line in Fig. 3(b), but the observed p-n junction is in a different location. The arrow indicates that both sides of n-regions are connected. This is the cause of high leakage current in the failed laser device.

**Figure 2.** Observation of semiconductor laser diode using Lorentz microscopy a) in focus, b) at defocus of -6.7 mm under-focus, c) at defocus of +6.7 mm over-focus.
4. Conclusions
We clearly observed the GaAs p-n junction using off-axis electron holography and Lorentz microscopy. The interface between \(1 \times 10^{19}\) cm\(^{-3}\) and \(1 \times 10^{18}\) cm\(^{-3}\) doped regions was clearly seen using electron holography, but was hardly visible with Lorentz microscopy. Off-axis electron holography is more sensitive to different dopant concentrations. We also observed the buried laser diode structure using these two techniques. The two-dimensional structure of the p-n junctions was clearly observed, which demonstrated an example of device failure analysis.

Figure 3. a) phase image of semiconductor laser diode b) enlarged phase image from dashed frame in Fig. 3(a). Designed location of p-n junction was at dashed line.

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