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X–ray Microdiffraction Studies of an Integrated Laser–Modulator System

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Abstract. We report the use of a spatially resolved x–ray microdiffraction technique for the structural study of an integrated laser–modulator system. The monochromatic (11 keV) x–ray beam microfocused to less than 1 μm in the vertical direction was obtained using a phase zone plate. The photon flux at the focal spot exceeded 3×10^{10} photons/s/0.01%bw/μm^2. The intense flux density and high spatial resolution of the focused beam was used to study the structure of a laser–modulator system, which is a 1–μm–wide and 1–mm–long multi–quantum well structure on an InP substrate. The superlattice d–spacing and the strain field in the direction normal to the diffracting planes were mapped as a function of position along the length of the device.

INTRODUCTION

With the availability of coherent, high–brilliance synchrotron radiation and advanced microfocusing optics (1), it is now possible to characterize materials at submicron length scales by x–ray diffraction. The x–ray diffraction technique is a nondestructive method and can be used to study crystallographic strain with high precision. The ability of x–rays to penetrate matter also makes it suitable for studying buried structures. Modern electronic and opto–electronic devices are smaller and more complex. Small changes in the structure within the device could change their performance considerably. Using a hard x–ray microprobe, one can directly map out the structure of an individual device over its entire volume nondestructively. In this article we report the use of a x–ray microbeam obtained by zone plate focusing to map the crystallographic strain and multilayer period in an opto–electronic device.

THE SAMPLE

The sample is an electro–absorption modulator/laser (EML), opto–electronic device supplied by Lucent Technologies. The EML is a monolithically integrated $In_{1-x}Ga_xAs_yP_{1-y}$ multiquantum well (MQW) structure grown on an InP substrate, as shown in figure 1. The width of the active region in the laser and the electro–absorption modulator regions is 1 μm. The device is grown by metal–organic vapor phase epitaxy (MOVPE) (2). The presence of SiO_2 pads patterned on the InP substrate causes the MQW to grow thicker in the laser region compared to that in the modulator region of the device.

EXPERIMENTAL

The experiment was performed at the 2–ID–D beamline at the Advanced Photon Source (APS) using monochromatized radiation from an undulator. The beamline has been designed to take advantage of the high coherence and low emittance of the APS to focus monochromatic x–rays to submicron size. The beamline has been described in detail previously (3). A schematic of the x–ray microscope is shown in figure 2. The microfocusing optic is a phase zone plate (PZP) with a focusing efficiency of 33% at 8 keV x–rays (4). The energy of the monochromatic beam used was 11 keV. The focal length of the PZP is 6.88 cm at that energy, and its diameter is 50 μm. The function of the order–sorting aperture is to allow only the first–order focused beam to reach the sample. The beam was focused at the center of a two–circle diffractometer arranged in horizontal geometry. The sample, mounted on an XYZ stage,

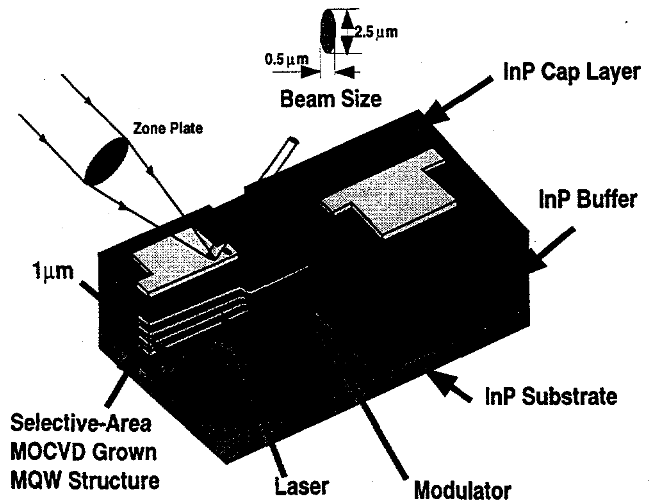

FIGURE 1. Schematic of the laser/modulator device

was accurately positioned in the center of the diffractometer with the help of two optical microscopes, one with its optical axis aligned with the azimuthal axis of the diffractometer and another lying in the diffraction plane.

To avoid any experimental artifacts in the diffraction data, the sample has to be very stable and stay in the center of focused beam at all times during the scan. In an experiment involving a θ–2θ scan, the sample may not be exactly in the center of the diffractometer, and the diffractometer usually has some wobble about its azimuthal axis. The net effect of all this is that the beam walks over the sample during the scan. This beam walking could be of several microns per degree of θ motion at some angles. In normal experiments, this is not very critical as the beam size is relatively large. To avoid this problem, one may scan the incident energy instead of the incident angle. In our experiment we could not do that because the zone plate focal length and focusing efficiency are not constants but functions of the incident energy of the x–rays. To solve the problem we used the high–resolution z–stage of the sample holder to compensate for any movement of the sample with respect to the axis of the diffractometer, by monitoring the Ga K fluorescence coming out of the sample. Figure 3 shows the Ga K fluorescence during a typical scan with z–compensation compared to without z–compensation.

The intrinsic zone plate resolution, which is 1.22 times the outermost zone width (5), is the diffraction–limited spot size that can be obtained. In this experiment the beam spot size was $0.5\,\mu$m in the vertical direction and about $1\,\mu$m in the horizontal direction. The footprint of the beam on the sample in the vertical direction was $0.5\,\mu$m and was $2.5\,\mu$m in the horizontal direction. It was larger in the horizontal direction because of the incident angle (Bragg). The divergence of the beam was 0.7 mrad. The incident photon flux was estimated to be about 3×10^{10} photons/s/0.01%bw/μm^2. Bragg scans (θ–2θ) were obtained at different points along the length of the sample. The position of the beam on the sample was continuously monitored during the Bragg scans by recording the Ga K fluorescence.

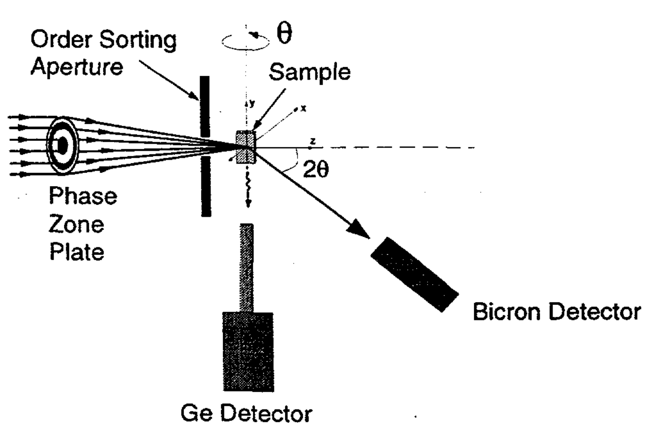

FIGURE 2. Schematic of the hard x–ray microscope

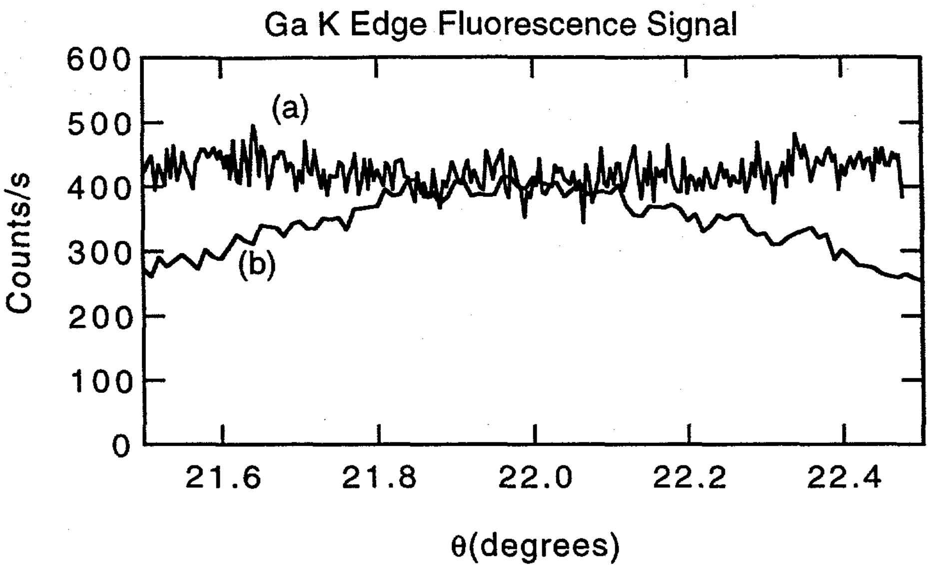

FIGURE 3. Ga K edge fluorescence signal during a Bragg scan (a) with z–compensation and (b) without z–compensation

RESULTS AND DISCUSSIONS

Figure 4 shows the θ–2θ scans of the diffractometer starting from the laser region and going into the modulator region. In addition to the InP (004) Bragg peak, satellite peaks from the MQW structure are also seen. Figure 5a shows the variation in the MQW period across the boundary between the laser and modulator regions. The period d_s was calculated by measuring the separation ϕ between the satellite peaks and using Bragg's law

$$\lambda = 2d_s \sin\phi. \qquad (1)$$

The thickness of the MQW is about 20% smaller in the modulator region compared to that in the laser region. Because of the lattice mismatch between the epilayer and the substrate, the zeroth order peak of the MQW is separated from the InP Bragg peak. The separation of this peak gives the degree of mismatch or strain relaxation in the direction normal to the surface. Figure 5b shows the degree of mismatch as a function of the device position. The laser region being thicker is more strain relaxed or has larger mismatch than the modulator region, which is relatively thinner.

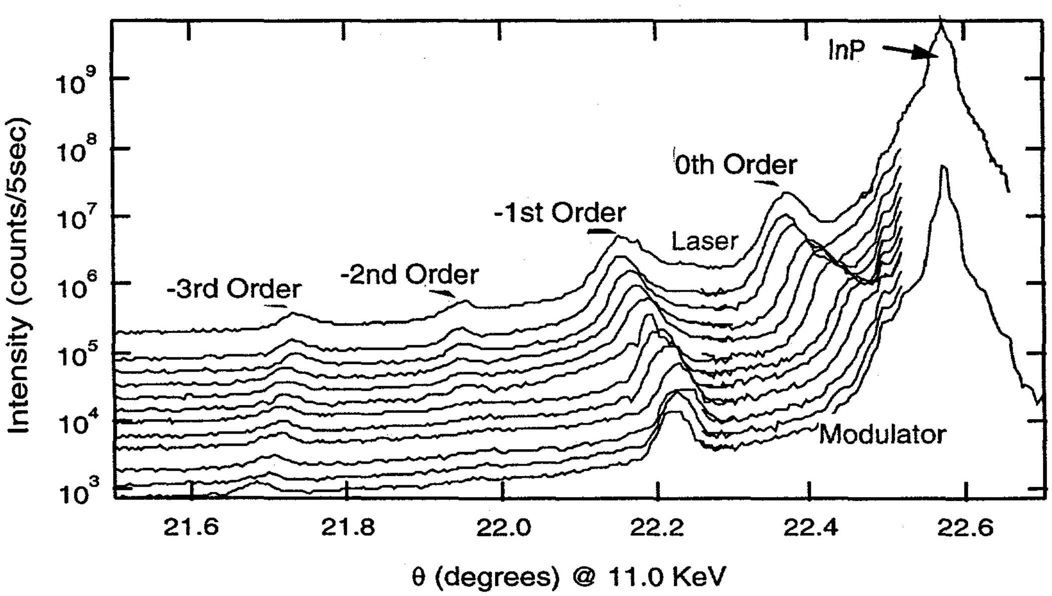

FIGURE 4. Bragg scans along the length of the device

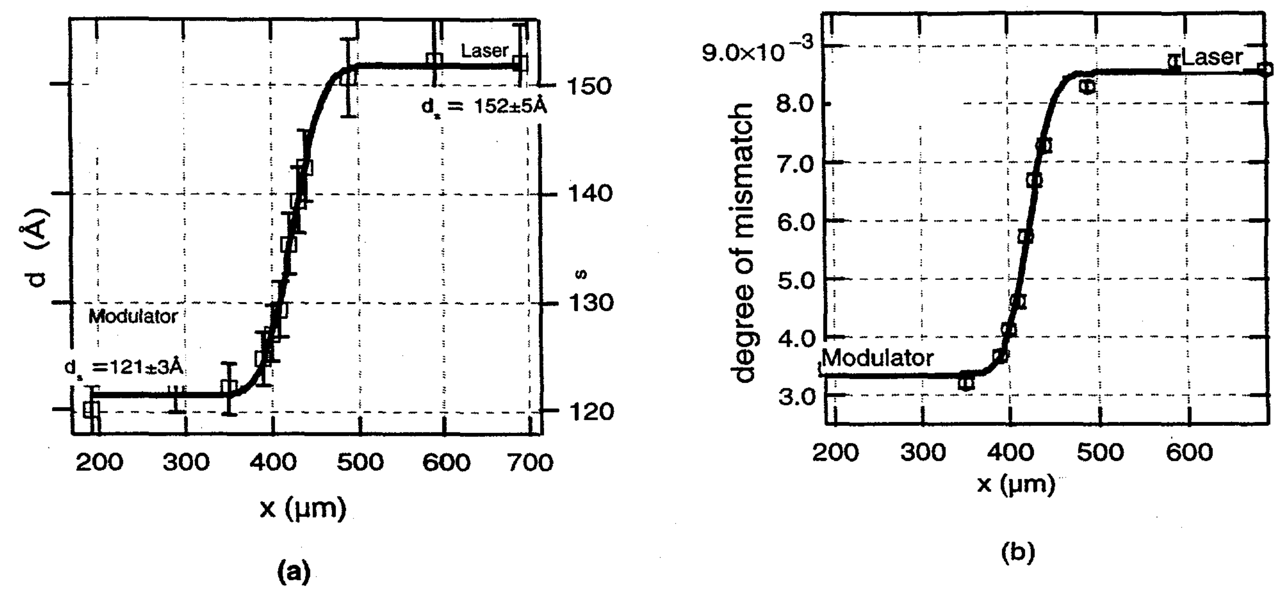

FIGURE 5. Variation of (a) MQW period and (b) lattice strain along the length of the device

This experiment demonstrates the high–resolution imaging capability of the x–ray microscope using phase zone plate as the focusing optic. The submicron spatial resolution of zone plates and the intense flux available from third–generation synchrotron sources like the APS can be used to nondestructively characterize miniature electronic and opto–electronic devices.

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