Ultrafast Strain Propagation in Epitaxial Thin Films

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Introduction

Recent advances in time-resolved x-ray technologies allow us to observe fundamental processes in condensed matter physics on short time scales. The relevant time scale for the impulse response of semiconductors following ultrafast laser excitation ranges from microseconds to subpicoseconds. Scientists at the MHATT-CAT beamline at the APS have previously reported on the generation and propagation of a picosecond coherent acoustic wave packet in semiconductors, which is one of the foremost responses due to the pulsed laser absorption [1-3].

Method and Materials

The sample used in this study was a 1.5-µm-thick (001) $Al_{0.3}Ga_{0.7}As$ epitaxial layer on (001) bulk GaAs, grown by molecular beam epitaxy by the Goldman Group at the University of Michigan. The AlGaAs layer was grown on a 200-nm GaAs buffer, with a growth rate of 0.5 µm/h. The composition (x = 0.3) was chosen such that the band gap of the AlGaAs (1.79 eV) is sufficiently greater than the laser photon energy at 800 nm, in order to make that layer transparent to the laser. The conduction band edge of AlGaAs is also sufficiently higher than that of GaAs in order to enable confinement of the photoexcited carriers in the GaAs while maintaining a reasonable lattice match. Finally, the thickness of the AlGaAs was designed to be approximately one quarter of the Pendellösung length at the desired x-ray energy. While this does not play a significant role in this work, it should allow one to measure transient changes in x-ray anomalous transmission that have previously been limited by the propagation time of the acoustic pulse into the crystal.

The AlGaAs/GaAs sample was oriented in the Bragg geometry to diffract from the symmetric (400) diffraction planes at 10 keV. Figure 1 shows the two distinctive diffraction peaks from the AlGaAs epitaxial layer and the GaAs bulk. The 50-fs, 0.75-mJ laser pulses at a wavelength of 800 nm are incident on the air side of the AlGaAs layer and deposit energy in a submicron region of the GaAs substrate. Following laser excitation, the time dependence of the x-ray diffraction is measured by using standard pump-probe techniques. Transient changes to the lattice due to acoustic phonons and thermal expansion are evident in the time-resolved diffraction efficiency. Differential thermal expansion in the GaAs due to the laser pulse is expected to generate an elastic response consisting of a unipolar compression wave that propagates in both media.

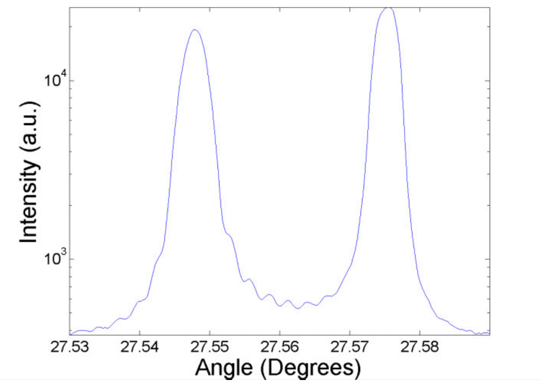

FIG. 1. Log plot AlGaAs/GaAs (400) Bragg diffraction peaks. The peaks are separated by approximately 0.0277º (≈0.01 Å).

Results

Figure 2(a) shows a time scan at an angle of 27.546°, just on the high-angle side of the AlGaAs peak. Since the acoustic velocity mismatch is relatively small, most of the compressive strain originating in the GaAs and traveling toward the AlGaAs is transmitted across the boundary. The initial increase in the intensity on the high-angle side of the AlGaAs peak is evidence of this compression (i.e., a concomitant shifting of the Bragg peak to a greater angle due to a decrease in the lattice constant). However, as the compressive strain pulse is reflected back from the AlGaAs/air interface, a π phase shift is introduced (due to the large impedance mismatch), giving rise to a tensile reflected strain pulse. This is evident in the decreased intensity (as the peak shifts toward smaller angles). We can deduce the same conclusion from the opposite behavior seen in the time-resolved diffraction efficiency measured at an angle of 27.5415° (on the expansion side of the nominal AlGaAs peak); see Fig. 2(b). The total time is consistent with the propagation of the strain pulse at the speed of sound and the 1.5-µm AlGaAs layer (4960 m/s).

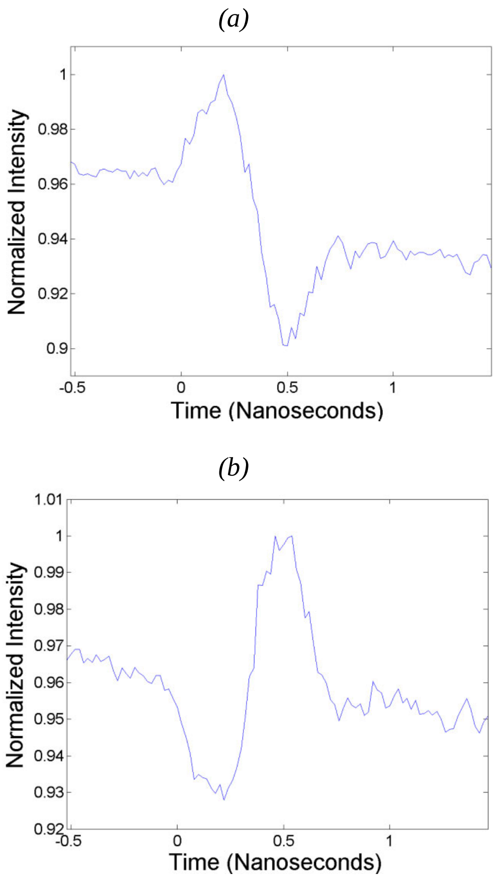

FIG. 2. Time scans from avalanche photodiode detection of the AlGaAs (400) peak on the (a) high-angle side and (b) low-angle side.

Figure 3 shows the temporal response in the diffraction efficiency on the low-angle side of the bulk GaAs. Initially, the thermal expansion and compression components of the strain cancel each other. As the compressive strain propagates away from the heated layer (into the bulk GaAs as well as the AlGaAs), the effect of thermal expansion becomes evident as an increase in the diffraction efficiency. The second increase in the diffraction efficiency is due to the return of the (now tensile) strain pulse that reflected off the AlGaAs/air interface, resulting in a higher intensity than that from the expansion contribution alone. The diffraction efficiency will again drop back down as the pulse travels deep into the bulk and, on a much longer time scale, as thermal diffusion establishes thermal equilibrium.

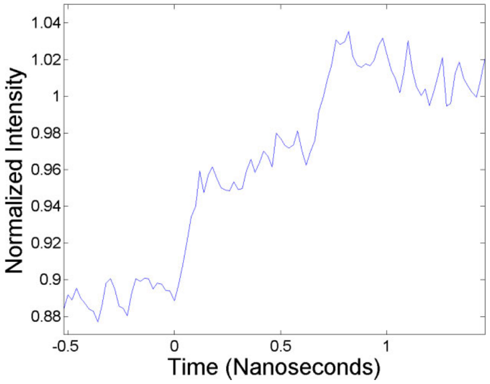

FIG. 3. Time-resolved diffraction (normalized to the peak intensity) measured on the high-angle side of the GaAs peak.

Discussion

From this work, we obtained a clear understanding of the behavior of ultrafast strain propagation across the bulk crystal and the epitaxial layer. More detailed analysis will allow the measurement of the wave vector (frequency) dependence of the Kapitza boundary impedance. Such studies can be extended to measurements on physical properties of thin films or even superlattices.

Acknowledgments

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