Student Paper

Quantum Cascade Lasers Characterization Using X-Ray

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Characterization of nano-scale superlattice (SL) based devices, such as quantum cascade lasers (QCLs), is very different from characterization of conventional interband laser or detector devices. X-ray diffractometry (XRD) is a powerful characterization tool capable of extracting useful information such as the strain, thickness and quality of the grown layers without introducing destructive damage on samples. Atomic-level scanning tunneling microscopes (STM) and transmission electron microscopes (TEM) have been used to characterize the growth quality of superlattice wafers. However, these methods yield observations that are localized and cannot view the entire structure. The x-ray scanning technique can observe not only the localized, but also the entire superlattice structure. By extracting special features and key parameters in x-ray diffraction (XRD) patterns, the epitaxial quality of QCL superlattices can be evaluated and correlated to the performance of fabricated QCL devices.

Fig. 1 shows an X-ray result of a strain-balanced InGaAs/InAlAs QCL. The Envelop of the satellite peaks indicates the overall structure, even after strain balanced, is still indium rich. The perfectly lattice matched condition can be achieved by decreasing the indium flow or increasing the gallium or aluminum flow, depending on which ternary structure is oppositely mismatched to the other. In a 1-D superlattice structure, the gradual change of a superlattice period can be observed in the Fourier spectrum as a reduction of the convolution length. The degradation of the superlattice periodicity eventually affects the number of the satellite peaks that are above the noise level and reveal in the spectrum. Besides a reduction in the number of observable satellite peaks, the linewidth of each peak may also gradually broaden, especially for higher harmonics.

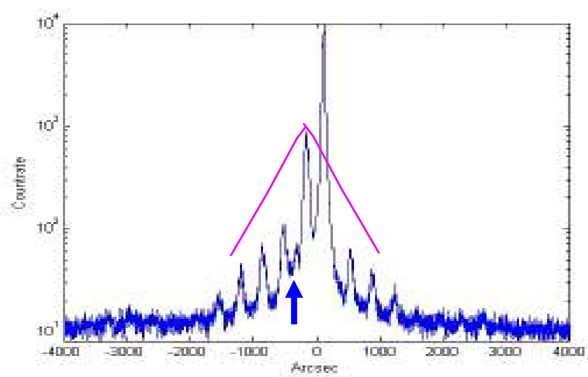

Fig. 1. X-ray scan spectrum of an InGaAs/InAlAs QCL with a small overall lattice mismatch in the Indium-rich side. The red curve shows the envelop of all the first order diffraction satellite peaks. The blue arrow indicates the sign of hetero-interface problems.

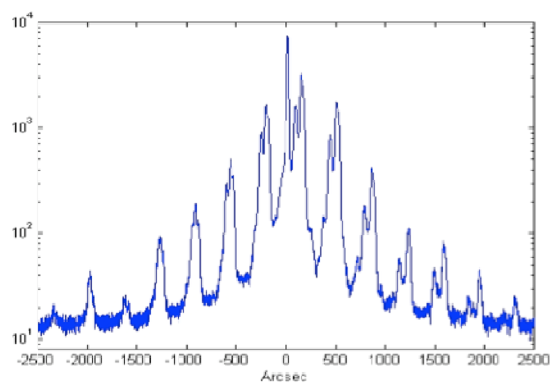

Fig. 2. X-ray spectrum of a QCL wafer with growth rate gradually changed during the growth.

Fig. 2 shows a QCL X-ray result that has two peaks, defined by two arrows, in each satellite bin. The separation between two peaks could be, though extremely rare yet possible, due to a result of a sudden change of the growth rate during the growth. Consequently, a new superlattice period associated with this new growth rate was grown, resulting in two superlattice structures in the entire structure. Also, the separation between two peaks as well as the corresponding linewidth gradually expands. A more profound separation at higher harmonics was observed. Similar to the case of a gradually change in growth rate, such a broadening effect is introduced by growth rate change and will produce a broadening in gain spectrum and reduce laser performance such as higher threshold and reduced L-I output. Nevertheless, there are other factors that affecting the linewidth of each satellite peak, including material degradation, lattice mismatch, and a low number of superlattice periods. Each factor shows its individual characteristics in the X-ray diffraction patterns. Details of their X-ray spectrum will be discussed

Since strain-balanced superlattices are composed of alternating compressive and tensile strained layers, the thicker layers are sometimes strained too much and lattice relaxation occurs - chemical bonds between atoms break and lead to serious degradation of periodicity. A very small percentage of relaxation can lead to a dramatic broadening of satellite peaks and a serious decrease in laser performance. Fig 3(a) shows the x-ray scan result of a strained superlattice sample with serious lattice relaxation. Nearly all satellite peaks are broadened. Fig.3(b) shows the simulated result with 200-period of InGaAs/InAlAs superlattice and ~2% relaxation in some of the thicker InAlAs layers. Through simulations, relaxations in InGaAs and InAlAs layers were found to show distinct patterns, which helps in determining which exact materials are causing the problems in a superlattice. As shown in Fig. 4, relaxation in InGaAs layers causes each peak to tilt upwards from the left to the right and relaxation in InAlAs causes individual peaks to tilt downwards from the left to the right.

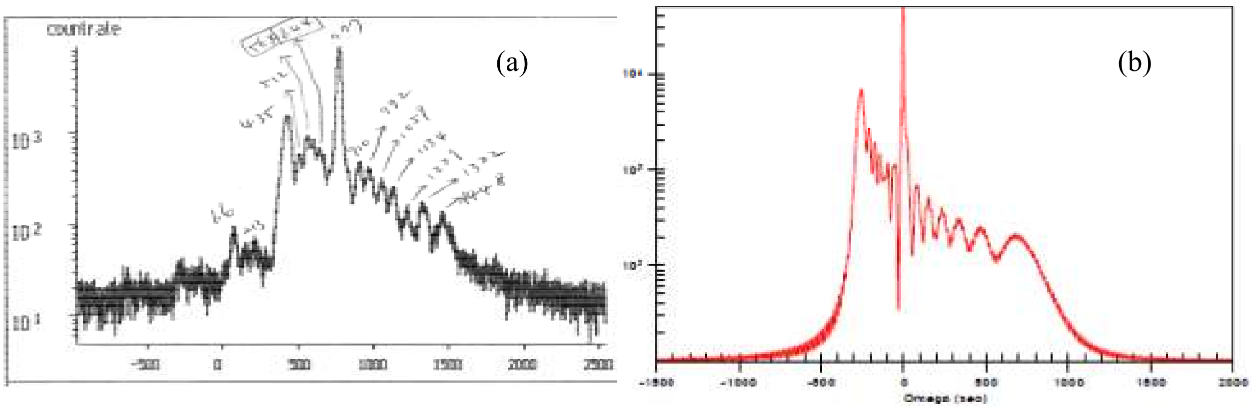

Fig. 3(a) Experimental x-ray scan of a grown superlattice with severe relaxation – we can identify that the problems are occurring in the layers of InAlAs because of the way the peak tilt. (b) Stimulated scan results of a super lattice with ~2% lattice relaxation tkin gplace in some of the thicker InAlAs layers.

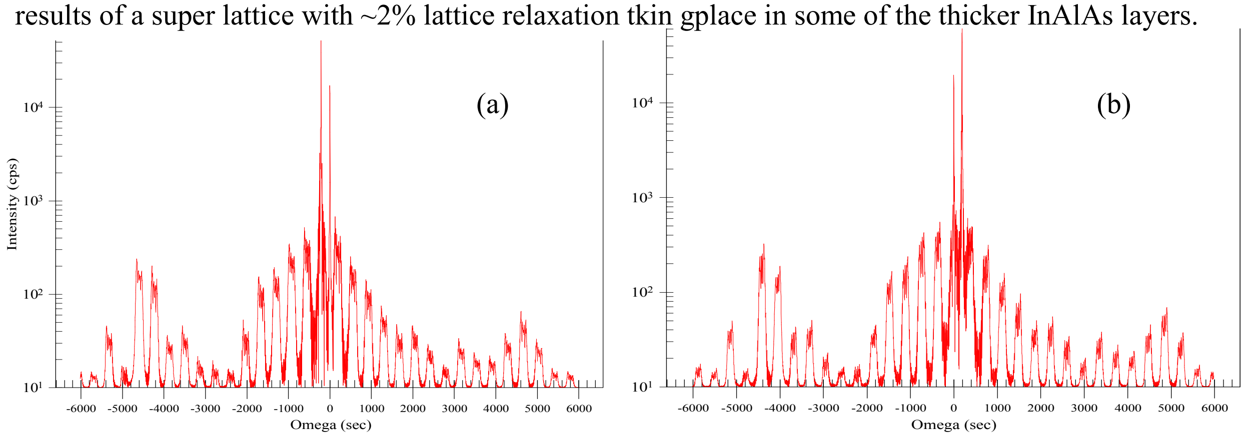

Fig. 4. (a) 0.5% relaxation in the thicker layers of the InAlAs material – note how the peaks tile downwards from the left to the right. (b) 0.5% relaxation in the thicker layers of the InGaAs layers – note how the peaks tilt upwards from the left to the right.

The X-ray analysis described above has a great impact on device performance. Due to limited space we would like to but cannot show X-ray scan results of two QCL wafers grown by MOCVD with the same growth structure and fabrication processes. One wafer produced RT CW high power (>1W single mode) QCLs while the wafer produced much worse performance. The curves look similar but from some key features differences we can tell that the atomic level lattice alignment is little bit off in the Gallium/Aluminum-rich side for the lower power one. The broadening of satellite peaks at higher harmonics also shows that the lower power one growth rate changed in a few periods. The asymmetric chirping happen more in the left hand side of satellite peaks in the lower power one suggested that the InAlAs material is primary one drifting in its growth rate. These thickness variations will broaden the QCL gain and that is detrimental to the performance of high–power QCLs. We expect that the methods can also be applied to other types of quantum devices such as quantum well infrared photodetectors (QWIPs) and strained-layer superlattice (SLS) detectors.