Wobble Normalization for Optical *In Situ* Measurements in Molecular Beam Epitaxy

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Optical techniques such as normal-incidence reflectance and atomic absorption spectroscopy are becoming popular methods for *in situ* monitoring of epitaxial layers during molecular beam epitaxy (MBE). Substrate rotation is used in virtually all device growth runs to average out spatial variations in source cell flux; sample wobble during rotation usually scales the desired optical monitoring signal by a periodic factor. The wobble effect comes from unwanted aperturing from the viewports (approximately 4×10^{-4} sr for a large pyrometer viewport), monochromator slits, or detector spatial nonuniformity. We have observed wobble-induced oscillations with amplitudes as large as 50% of the average normal-incidence optical reflectance signal (ORS) for substrate wobble angles on the order of $\pm 0.5°$. Atomic absorption measurements are also susceptible to these effects when the ultraviolet light beam used to measure the absorption is reflected off the sample at a shallow angle (rather than only passing above the sample surface). Reflection mode has the advantage of measuring layer thickness as well as atomic flux, but small wobble effects are significant because the intensity of the signal is critical in interpreting the data.

A number of wobble compensation techniques are possible, including simply averaging out the signal over the rotation period (with corresponding loss in time resolution) and more sophisticated digital signal processing. We have made use of the periodic nature of the wobble effect to carry out real-time normalization of optical signals, somewhat similar to the phase-locked epitaxy technique. Specifically, a synchronization signal is generated by measuring reflectance from a piece of transparency film with eighteen "trigger" stripes encircling the substrate manipulator rotation magnet. (We generated the trigger signal with an interlock photosensor that was part of the transfer system for our machine.) Two of the stripes are about 30% closer together than the others to provide a rotation phase reference point for determining a zeroth trigger. A normalization curve can be obtained by averaging several rotations' worth of data with the sample in an otherwise constant state, such as during a stopgrowth or buffer layer growth. This reference curve must be acquired for each new substrate, as mechanical variations in substrate holders are sufficient to produce large changes in the shape and phase of the wobble effect. Subsequent data points can then be normalized by monitoring the optical signal and the trigger signal simultaneously, and analyzing the trigger signal in real time to determine the appropriate normalization factor. Our initial efforts have found that this procedure reduces the wobble effect in ORS by a factor of 8 or more, leaving variations of only $\pm 1\%$ in mostly random noise. In atomic absorption measurements, the wobble effect was typically reduced by a factor of 10. Key factors in making this technique work have been (1) careful budgeting of computer time during data acquisition in order to perform the normalization in real time, (2) use of several triggers per rotation to allow accurate normalization even for rotation speed variations on the order of $\pm 15\%$, and (3) use of a zeroth trigger to recover from accidental loss of trigger synchronization.

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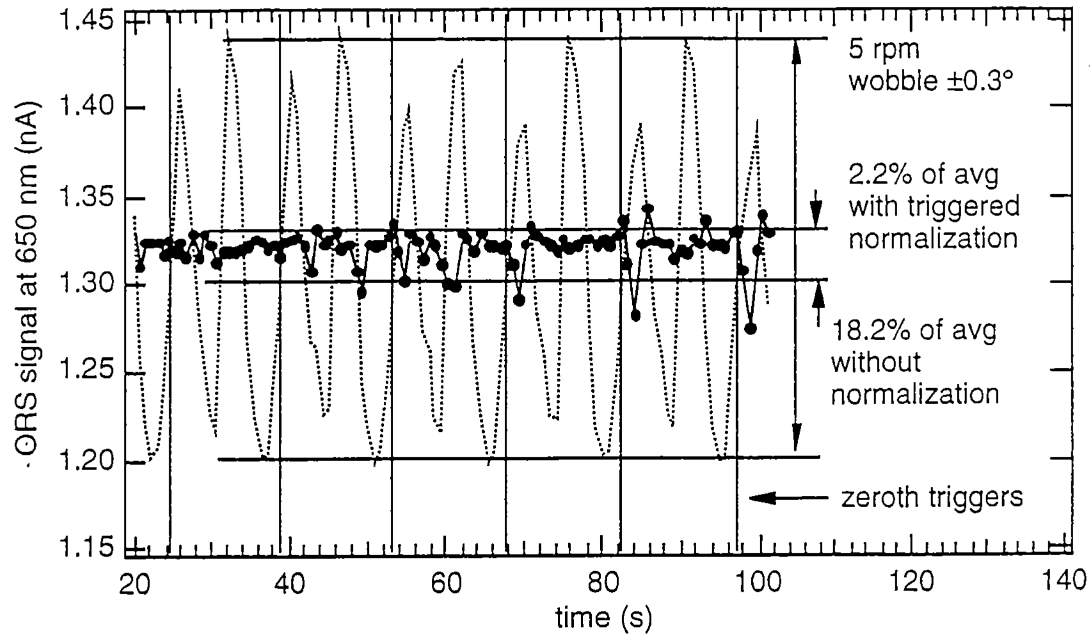

Fig. 1 Optical reflectance spectroscopy (ORS) with and without synchronized trigger normalization. The data are taken at 650 nm from a GaAs sample rotating at 5 rpm. The larger excursions in the normalized signal after zeroth triggers correspond to rubbing between the rotation shaft and heater assembly in the manipulator.

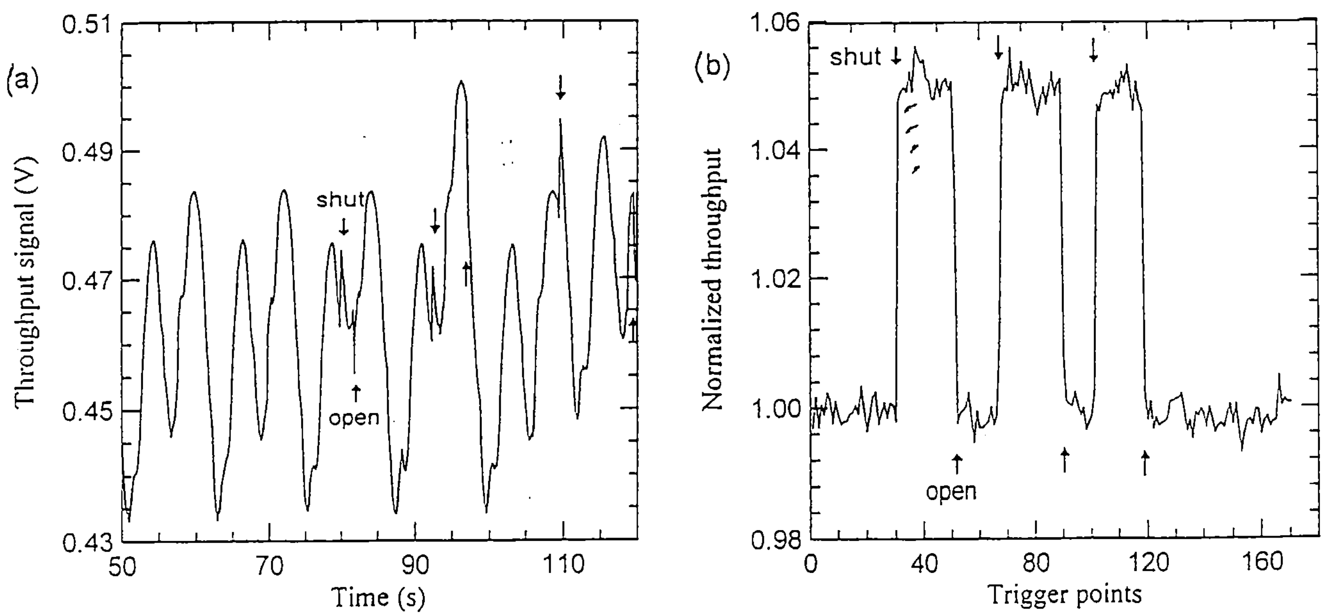

Fig. 2 Throughput of beam from a Ga vapor hollow cathode lamp reflected at 78° from two different GaAs wafers rotating at 5 rpm showing the atomic absorption signal at Ga cell shutter flips (indicated by arrows): (a) raw data showing the effect of wobble, and (b) real-time triggered and normalized data showing a tenfold reduction in the wobble effect. The approximate time between trigger points in (b) is 0.67 s. The wobble was measured as ±0.20° and ±0.45° for the samples used in (a) and (b), respectively.