X-ray of High Order Planes, Pathway for HBT Control

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Abstract

High volume HBT (Heterojunction Bipolar Transistor) production benefits from non-destructive measurement techniques to verify the quality of every product wafer. X-ray diffraction is non-destructive and sensitive to layer thicknesses and compositions. The thin layers typical of HBT designs yield weak diffraction intensity, which are overwhelmed by the signal from the substrate in the conventional (004) orientation. We have found that by diffracting from the (117) planes, much more information can be obtained. As the HBT layer peaks move away from the substrate signal this enables the in-line measurement of HBT product wafer characteristics, such as base doping[1]. In this paper, we develop a new curve fitting methodology, and demonstrate the precise measurement of the base doping of HBT wafers in the production line for the first time. This technique is demonstrated to measure base doping changes in production as small as 1.8%.

INTRODUCTION

The continual demand for tighter specifications in the production of state-of-the-art GaAs HBTs requires improved measurement tools to ensure the quality of each product wafer. Historically, in each production lot a wafer is destructively used to characterize the parameters of large area HBTs. This device contributes a wealth of information confirming the quality of production material. Non-destructive tools then confirm that there have been no deviations from this reference HBT throughout the production lot. Generally in-line metrology for HBTs is composed of contactless resistance mapping and surface haze monitoring systems. In this work we have developed a novel in-line XRD methodology that is capable of measuring the base doping of product HBT wafers. This system is rapid (15 minutes), automated, and non-destructive. Base doping is a key parameter controlling the base sheet resistance, DC gain and a multitude of RF performance parameters.

This XRD technique further complements HBT measurement of the base sheet resistance. By independently measuring the base doping using x-ray diffraction, the doping and thickness components of the base sheet resistance can be separated.

This technique is based on X-ray diffraction measurement of the base lattice constant. The lattice constant of the carbon doped base layer is known to contract in proportion to C doping[2]. Typical HBT base material has a C doping of 4E19 cm^{-3}[3]. For the conventional (004) reflection

this C density provides a shift of roughly +75 arc seconds between the GaAs substrate and the C-doped base. This shift is observable for bulk layers, but layers typical of state-of-the-art HBTs (<150 nm) disappear under the substrate peak. The peak separation can be increased to +400 arc seconds by utilizing the asymmetric (117) reflection [1]. Figure 1 presents the (117) diffraction data from a representative HBT, where the signal from the base layer, indicated by the arrow, lies to the right of the sharp substrate peak. This separation from the intense substrate peak allows the base carbon doping of product HBT wafers to be measured.

In the following sections the sensitivity of the base peak position with carbon doping is demonstrated. The oscillating fringes present in the structure are shown to be an indicator of the subcollector and collector thicknesses. Repeated measurement and curve fitting of a single wafer is tested over 250 days, where the sigma variation of base doping is ±0.7%. Finally and most importantly the system is able to identify slight base doping adjustments between lots as small as 1.8%.

RESULTS & DISCUSSION

A. Fitting Algorithm

A fitting algorithm is necessary to reduce the raw X-ray data of Figure 1 to material parameters such as base doping.
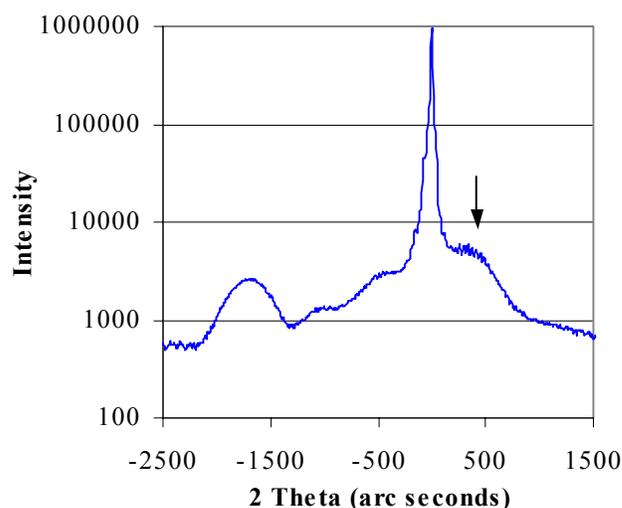

Figure 1. (117) X-ray diffraction data from an HBT. The arrow points to the peak from the carbon doped base layer.
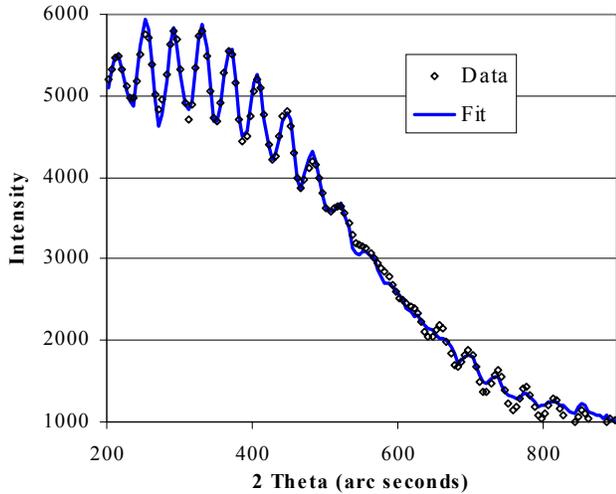
Figure 2. Close up of the base region showing the close fitting to the peak and oscillations.

Off-the-shelf X-ray diffraction simulation programs based on layer thicknesses and compositions do not fit the data closely enough to follow the small changes relevant to a production environment. This may be a result of the highly relaxed and defective InGaAs contact layer on the sample surface.

Alternatively, we have developed software to fit the base region of the X-ray curve shown in Figure 2. The curve fitting consists of 3 parts. The substrate peak shape is obtained from a blank GaAs wafer. Added to the substrate peak is a gaussian peak representing the base layer. Finally a $\sin(x)/x$ function is used to fit the oscillating fringes [4]. The advantage of using these simplified functions is that the effects of the parameters on the simulated data are largely isolated from each other. For example the gaussian peak position has a very different affect on the calculated data than does the gaussian peak width or the $\sin(x)/x$ period. This simplified fitting can closely follow the diffracted curve enabling the base doping to be tracked.

B. Calibration of the Fit Parameters

Off-the-shelf X-ray simulation programs solve the dynamical X-ray diffraction equations for a given sample structure, where the fit parameters are the layer thicknesses and compositions (i.e. doping). In the simplified fitting algorithm adopted here, the fit parameters are not directly related to the material but are simply the peak position, peak intensity, etc. of the measured data. Furthermore, the base peak position determined from a fit to an HBT curve can depend on layer thickness. The position may not be the same as a bulk base layer sample having the same doping level. The layer thickness and overlapping signal from other layers of the HBT will shift the appearance of the peak. The sensitivity between the fit parameters and material parameters needs to be calibrated by analyzing several HBT wafers
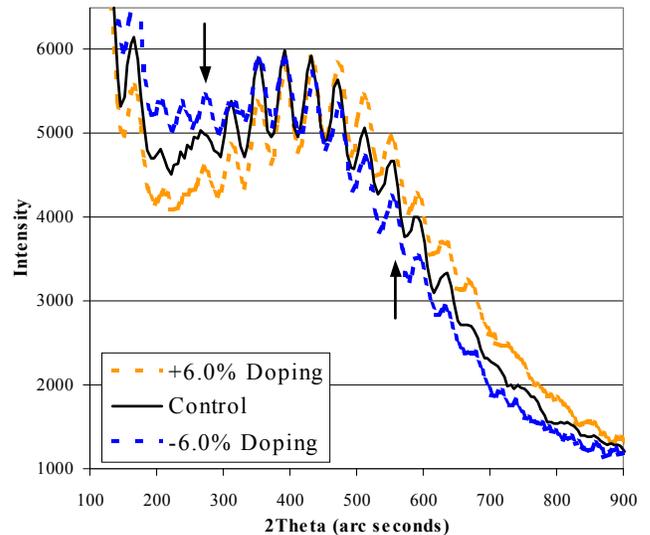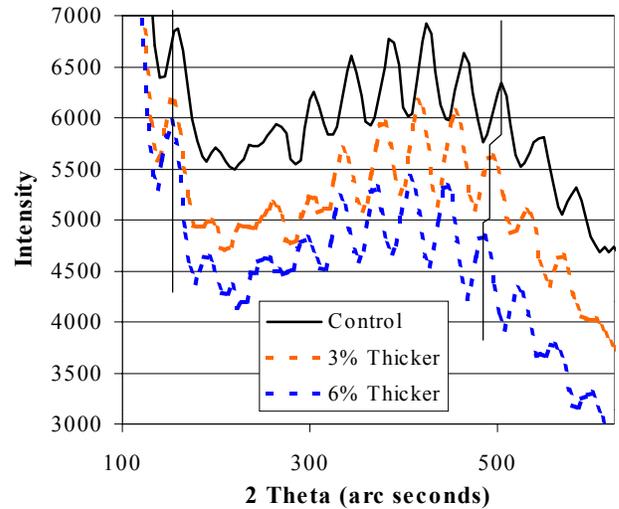

Figure 3. An increase in the subcollector and collector thickness clearly reduces the period of the oscillation in (a). Increases in the base doping shift the intensity toward the right in (b).

grown with intentional layer variations. These changes allow the shifts in the X-ray data to be related to changes in the material. Most parameters, such as emitter thickness or composition, were found to have a negligible effect on the region shown in Figure 2. The position of the base peak is determined by the base doping, and the oscillating fringes are related to the combined thickness of the subcollector and collector layers. These oscillations are a result of reflection from material interfaces analogous to those observed more commonly with optical reflectivity.

Intentional changes to HBT wafers were used to relate shifts in the X-ray data to material changes. The fringe spacing decreases with subcollector and collector thickness
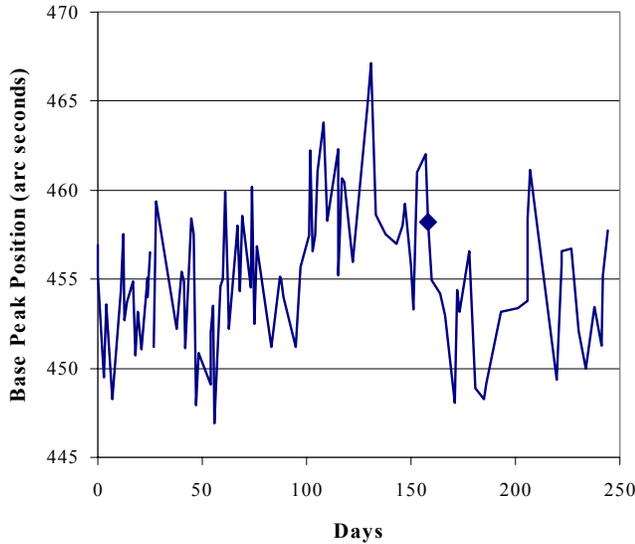
Figure 4. Base peak position measurement repeatability of an HBT wafer over 250 days. The X-ray source was replaced on day 160, indicated by the diamond. The intensity increased by 50% but the data shift is negligible.

Figure 5. Base peak position across production lots where doping was intentionally decreased in two step by 1.8% each.

as shown in Figure 3 (a). The fringes are aligned at the left of the figure and highlighted by the added line. A second line is drawn after 9 periods. The increased thickness reduces the interference fringe period moving the line following the 9th period to the left. The thickness change of only 3% is visible over these 9 periods. A collector thickness change of 3% has direct implications for HBT device properties such as collector breakdown voltage and Ft (maximum frequency of oscillation).

Subtle changes in base doping are also readily observable. The result of HBTs grown with intentional changes in base doping is plotted in Figure 3 (b). An increase in doping shifts intensity towards higher angles. The arrows in Figure 3 (b) highlight the fall in intensity at 250 arc seconds and increase in intensity at 550 arc seconds as the doping was increased and the peak shifts to the right. The extracted peak position is 368, 400, and 433 arc seconds for the –6.0%, control, and +6.0% doping samples respectively. The doping level was determined from Hall measurements of bulk base layer samples.

A final question remains regarding instrument noise and precision over repeated measurements. This data is presented in Figure 4. Here, the same sample was measured over 250 days, and the base peak position is plotted. The average value is 455 arc seconds with a sigma of ±4.0 and a range of 20. While the shift in data presented in Figure 3 (b) may appear small, the measurement noise is well below this shift. The base peak position noise of ±4.0 translates into ±0.7% of doping.

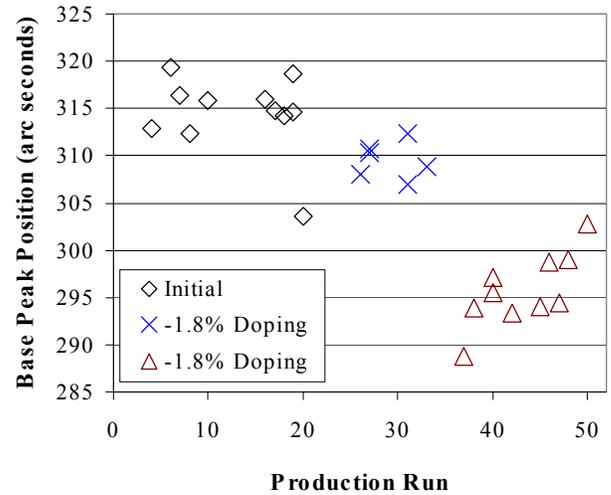Included in Figure 4 is data spanning the installation of a new X-ray source. The diamond indicates when the new

source was installed. The new source provided 50% increased diffracted intensity. This large change in intensity had only a minimal impact on the base peak position.

C. Data from Production

The data from calibration samples and control wafers has shown that base doping changes considerably smaller than 5% can be observed. For full production readiness the measurement system must be capable of observing small drifts within production and small corrective changes made between production lots. This is examined in Figure 5, which includes data spanning 50 runs taken from wafers from a distribution of pockets. The base doping was fine tuned between lots by -1.8% at the 23rd and again at the 34th run. The data shows that run-to-run and across wafer pockets there is a variation of less than 10 arc seconds. In the midst of this real world variation the initial -1.8% change is just visible while the –3.6% change is easily resolved.

CONCLUSIONS

The lattice contraction from C doping of an HBT base can be measured on product wafers non-destructively by utilizing diffraction from the (117) planes. This measurement is shown to be capable of measuring 1.8% changes in base doping in a production environment. The system is fully automated and takes only 15 minutes, making the process ready for high volume manufacturing. HBT base doping can now be verified non-destructively on a run-to-run basis for the first time.

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ACRONYMS

HBT: Heterojunction bipolar transistor
MOCVD: Metal-organic chemical vapor deposition
RF: Radio frequency
SEM: Secondary electron microscope