Translating Epi Structures into Growth Recipes — Manufacturability Concerns

Guoliang Zhou and Mark Borek

Skyworks Solutions, Inc., 20 Sylvan Road, Woburn, MA 01801, guoliang.zhou@skyworksinc.com

Keywords: manufacturability, pHEMT, MBE, growth temperature, leakage

Introduction

Design and optimization of a compound semiconductor device usually start with design and optimization of an epi structure. An epi structure that is defined by a material spec is typically an ideal structure. Any imperfections introduced by a growth process such as spreading of doping profiles and intermixing of heterostructure interface are usually not defined in a material spec. The process of generating a growth recipe is a process of interpreting a material spec. Those growth processes related imperfections undefined by the material spec must be taken into account during recipe creating process, and the translation is not always unique. The complexity of an MBE growth recipe will not only depend on the required device structure, but also on reactor hardware (such as cell configurations), and other important considerations such as manufacturability of the products. The way how the recipe is setup can have huge impact on the robustness of overall production process. In this paper, we will use pHEMT structure as an example, to discuss the strategy and concerns (especially manufacturability aspects) associated with MBE recipe generating process.

Results & Discussions

When designing and optimizing an epi structure, the focus has always been on how to achieve the best possible material quality. The best material quality means minimum crystal defect density, abrupt and smooth interfaces, and minimum impurities. A common heterostructural device such as pHEMT consists of at least two different types of materials. The growth condition that is optimized for one material type may not necessary be the optimum condition for another one. When translating an epi structure into a growth recipe, we will have choices to either tailor the growth condition for each individual layer within a growth recipe or choose a unified but compromised growth condition for all the layers. In either scenery there are tradeoffs and limitations. In some cases, although the growth condition can be optimized for each individual layer, it requires transitions to switch growth condition from one layer to another. Such transition usually requires a growth stop. In other cases when individual layer thickness is too thin, or there are other limitations such as source configuration, strict doping or contamination requirements, etc., insert a growth stop may not even be possible.

One of the important aspects, which is often overlooked during initial epi structure design process, is manufacturability. An epi structure that has been optimized for achieving the best performance of a device during development phase may not always yield well consistently after transferred into production phase. This is usually due to that manufacturability aspect is not taken into account during the initial device design and optimization phase. Here, we use a typical pHEMT device (shown in Fig. 1) as an example, to illustrate how different ways to translate an epi structure into a growth recipe can make huge difference to overall production yield and device performance.

Fig.1 shows a typical pHEMT device used for switch application. The structure consists of active device layers, such as n-GaAs layers, InGaAs channel layer, AlGaAs Schottky and barrier layers. The optimal growth conditions for different material are usually quite different. In this case, the strained InGaAs channel layer requires relative lower growth temperature, while AlGaAs Schotkky layer is preferred to be grown at higher temperature in order to achieve the best material quality. Si delta-doping, on the other hand, requires lower growth temperature for retaining sharp profile. When generating a production recipe, material quality is not the only important factor that need be considered. Other factors such as production throughput (the total cycle time of a growth process), yield consistency (sensitivity to variation of process condition), reactor configuration, etc. can also have high impact to overall product quality and cost. The common approach to grow the pHEMT epi shown in Fig. 1 is growing both lower AlGaAs spacer and InGaAs channel at relative lower temperature to retain the smoothness of InGaAs layer and minimize dislocation generation and Si delta-doping spreading into the channel. The growth process will be paused for a short period of time (so called growth-stop) after InGaAs growth to allow temperature ramping up to an optimal value for AlGaAs, and then continue for the remaining layers. This process, although can be optimized for the best material quality, shows high sensitive to small variation of process condition, which can result a very inconsistent device and yield performance.

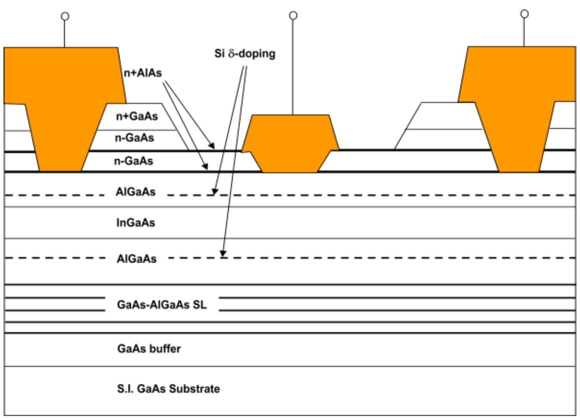

Fig.1. A typical AlGaAs/InGaAs double hetero-structure pHEMT device

Fig. 2 shows SIMS depth profiles of Si from four pHEMT epi wafers grown at normal growth condition with a slight variation of growth temperature (in the range of 30ºC). It is very clear that the top delta-doping spread is very sensitive to even 10 ºC of growth temperature variation. Such high sensitivity is very prone to gate leakage failure for final finished devices, which will result inconsistent yield. The bottom delta-doping peak, on the other hand, remains a sharp profile regardless temperature change. The spreading of Si delta-doping profile is driven by two mechanisms: surface segregation and bulk diffusion. The activation energy of a typical bulk diffusion process is much higher than that of surface segregation. At the typical growth temperature range of 450-650ºC for our pHEMT structure, the bulk diffusion process is still very limited, and its contribution to doping spreading can be ignored. Surface segregation mechanism, however, due to its much lower activation energy, can significantly broaden Si doping profile under certain growth conditions. In our pHEMT example, the bottom delta-doping profiles remain unchanged with the variation of growth temperature, indicating that surface segregation process is still very limited at the lower end of our growth temperature range. The high sensitivity of top delta doping profile to our growth temperature for AlGaAs Schottky layer reveals that the growth condition must be very close to the cusp of triggering surface segregation process. From manufacturing perspective, this approach is not the best choice for delivering a consistent product and yield performance.

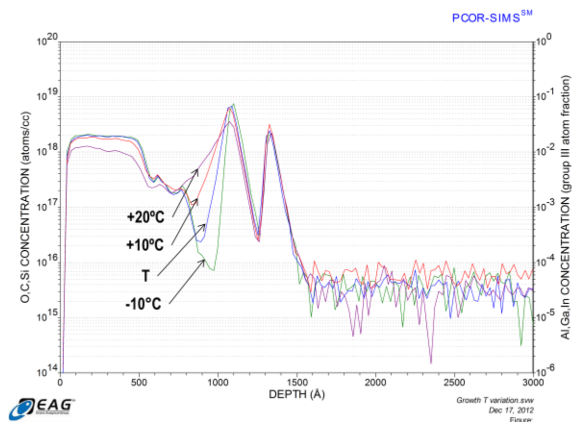

Fig.2. SIMS delta-doping profiles of Si from four pHEMT epi wafers grown at slight different temperatures. T is a typical growth temperature used for pHEMT.

By taking into account of manufacturability during the early stage of epi design phase, the thought process can be quite different. Although the complexity of the recipe generating process will be greatly increased, the overall benefit to production yield, cost, and quality control is substantial. In this paper, we will discuss the general requirements and guidelines for translating an epi structure into an MBE growth recipe. Particularly, we will concentrate our discussion on manufacturability aspects of MBE recipe defining and generating process, and share the lessons we have learned at Skyworks and the strategies we have been using in order to achieve consistent yield and device performance.