A Comparison of MOVPE and MBE Growth Technologies for III-V Epitaxial Structures

Rodney Pelzel, Ph.D.
VP, Wireless Technology

IQE, 119 Technology Drive, Bethlehem, PA 18049, Phone: +1 (610) 332-3218, Email: rpelzel@iqep.com

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Abstract

Which is better, Molecular Beam Epitaxy (MBE) or Metal-Organic Vapor Phase Epitaxy (MOVPE)? The obvious answer is "it depends." From a purely technical perspective, choosing the best growth technology is based on the precise details of the grown structure and end application. Commercially, the appropriate choice is strongly impacted by the cost profile for each technique and the specific capacity profile inherent to a specific product type. However, the choice of the appropriate technique is often mired by a complicated mix of "half-truths", folklore, and historical notions that are applied by both sides of the debate. A survey of the technical and commercial strengths and limitations of each technology based on first-hand expertise will be provided. Throughout, certain common notions will be challenged.

INTRODUCTION

Epitaxial growth of III-V materials is a cornerstone technology for the wireless, optical, and photovoltaic industries. Structures such as PHEMTs, HBTs, VCSELs, and multi-junction solar cells require the purity and crystalline quality that only epitaxial growth can provide. For III-V epitaxy, there are two technologies that are used in high volume, molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE). Within the epitaxial community there has always been debate over which technology is "better."

Before, attempting to elucidate the "better" question, it is necessary to provide a brief summary of each technique.

MBE

MBE is growth on a heated substrate in ultra-high vacuum (UHV) environment (base pressure ~1E-9 Torr) typically using elemental sources. The UHV environment not only ensures material purity, but it also results in highly directional elemental beams (no carrier gas required) due to the inherently long mean free paths. Layered structures are achieved by shuttering. In addition, valved sources are typically used for group V materials due to their relatively high vapor pressures. It is also possible to use compound decomposition sources (e.g., GaTe for Te doping), gas sources (e.g., CBr4 for C doping), and plasma sources (e.g., N plasma for nitride applications).

MOVPE (aka OMVPE or MOCVD)

MOVPE also grows on a heated substrate but in a much different pressure regime than MBE (typically 15 to 750 Torr). Rather than elemental sources, MOVPE uses more complex compound sources, namely metal-organic sources (e.g. tri-methyl Ga, In, Al, etc.), hydrides (e.g., AsH3, etc.), and other gas sources (e.g., disilane). In MOVPE, the reactants are flowed across the substrate where they react resulting in epitaxial growth. In contrast to MBE, MOVPE requires the use of a carrier gas (typically H) to transport reagent materials across the substrate surface. Layered structures are achieved by valve actuation for differing injection ports of a gas manifold.

COMPARISON OF THE TECHNIQUES

Table 1 provides a comparison of MBE vs. MOVPE.

TABLE I
COMPARISON OF MOVPE AND MBE

Category	Characteristics of MOVPE	Characteristics of MBE
Technical	High growth rate for bulk layers	Fast Switching for superior interfaces
	Growth near thermodynamic equilibrium, excellent quality / crystallinity	Able to grow thermodynamically forbidden materials
	Ability to explicitly control background doping	No hydrogen passivation, no burn in inherent to MOVPE
		Uniformity easier to tune, largely set by reactor geometry
Commercial	Shorter maintenance periods	Longer individual campaigns, less setup variability
	More flexibility for source and reactor configuration changes	
	Higher safety risk, increasing scrutiny of legislative bodies worldwide	Lower material cost / wafer
	Economic to idle. Overhead cost scales with run rate	Overhead does not scale with run rate. Contribution per wafer increases with wafer volume

Based on Table 1, one can start to make some generalizations about different classes of devices. Some examples will be discussed next.

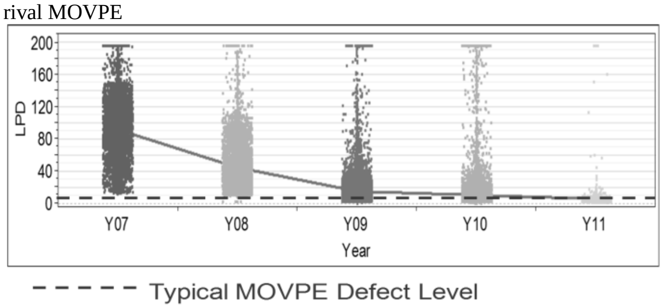
PHEMTs

For PHEMTs, MBE is still a dominant technology. MBE's foothold has been based on the switching characteristics making it ideally suited to structures with thin and alternating layers. However, MOVPE has been able to grow high quality PHEMT material. In fact, within the IQE group, we have demonstrated the expertise to match device performance between MBE and MOVPE for PHEMTs. For certain applications, the exact device specifics dictate the superiority of one technique vs. the other (e.g., buffer characteristics), and often MOVPE material is shown to have specific advantage for certain high frequency characteristics.

When the device performance is epi technology agnostic, then other factors come into play and can often be yield limiters. Two such characteristics are defectivity and uniformity.

Defectiivity is often cited as a key characteristic by those preferring MOVPE for PHEMT growth. In fact, one notable absence from Table 1 is defectivity. It has been a long held belief that MOVPE will always be able to provide lower defect levels. In fact, text books on epitaxial technology state this difference as inherent to the techniques – a scientific fact [1]. The reality of the situation is that MBE has made significant strides over the last 5 years and now has a capability rivaling MOVPE. A first hand example of this has been achieved by the IQE group through appropriate equipment design improvements for its MBE reactor fleet. Figure 1 shows how we have been able to use such innovation to reduce defectivty of MBE-grown material. It is noted that the IQE group has been able to achieve this improvement by employing many of the techniques and lessons learned from its MOVPE experience. This underscores that MOVPE has significantly benefitted from more extensive engineering effort from equipment vendors.

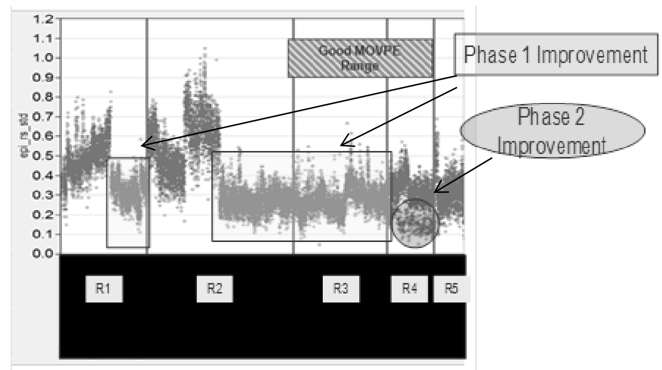
Figure 1: Defect Improvement Example for MBE for a typical volume product for one of IQE's MBE sites. The reduction in LPD year-on-year is the result of concerted equipment engineering effort. The current levels rival MOVPE



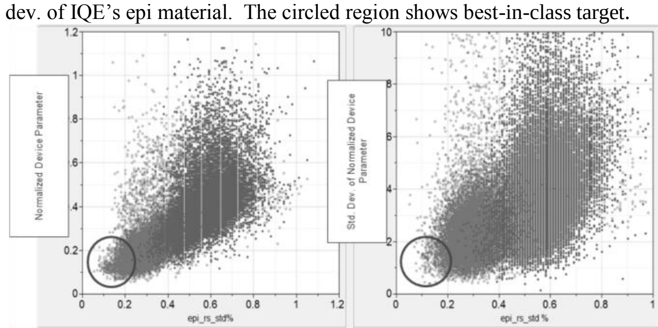
PHEMT uniformity is a critical parameter that is directly linked to yield for key parameters such as pinch-off voltage (Vp). Uniformity can be strongly impacted by the precise device structure, so it is important to make sure that an appropriate comparison of like structures is considered to assess how the uniformities of the techniques compare. Within the IQE group, the best within wafers have been achieved using MBE. Figure 2(a) shows an example of sheet resistance (Rsh) uniformity improvement over a subset of the IQE group's MBE reactors.

Figure 2: Uniformity comparison between MBE and MOVPE.

(a) Example of a 2-stage uniformity improvement effort for 5 of IQE's MBE reactors. The runchart highlights where the Phase 1 improvement was implemented on each reactor. The Phase 2 circle shows a further improvement. Ultimately a 2x improvement in Rsh uniformity was achieved



(b) Scatter plot of normalized customer device parameter (left plot) and normalized device parameter std. dev. (right plot) vs. the delivered Rsh std. dev. of IQE's epi material. The circled region shows best-in-class target.

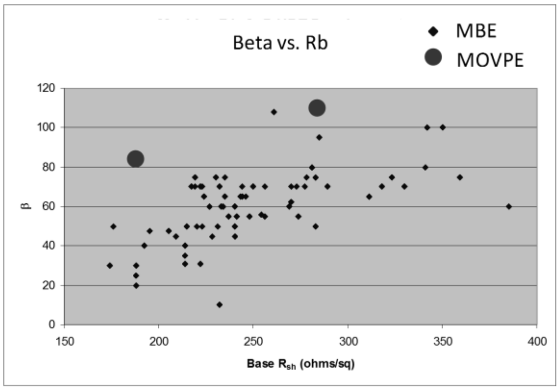


Although MOVPE, in principal, offers more degrees of freedom to tune uniformity, MBE is simpler to tune, and provided the geometry of the equipment is appropriate (the case for all currently available multi 6" platforms), the uniformity is easily tuned and typically superior to MOVPE.

InGaP HBTs

Growth of InGaP-based HBTs is almost entirely dominated by MOVPE. There are two key device performance characteristics that have led to this dominance, namely the ratio of Gain (beta) to Base sheet resistance (Rb) and the base-emitter ideality. The beta / Rb ratio serves as a figure of merit for the device. Figure 3 shows a comparison of typically achieved beta / Rb ratio for MOVPE material compared to MBE-grown material by the IQE-group.

Figure 3: Beta vs. Rb for InGaP HBTs. The small diamonds correspond to MBE material. The large circles show "typical" MOVPE values. The MOVPE material has a superior beta / Rb relationship that is preferable to the MBE material.



The beta / Rb ratio is better for MOVPE due to the quality of the C-doped base achievable in MOVPE (c.f., Table 1). As noted the base-emitter ideality is also preferable for MOVPE material as compared to MBE. This is suggestive that the base-emitter (GaAs:C – InGaP:Si) is better suited to growth by MOVPE. Again, this may be a consequence of MOVPE growing closer to thermodynamic equilibrium than MBE. Interestingly, this highlights a flaw in the generalizations listed in Table 1, namely that MBE always has preferable interface / switching characteristics. This is not a universal truth, especially for mixed group V growth.

It is noted that due to the success of MOVPE for growing InGaP HBTs that the growth of this structure by MBE was not fully explored. It is conceivable that future HBTs may benefit from some of what MBE can offer (e.g., no burn in due to the lack of hydrogen). As such the reader is cautioned, again, on taking what conventional wisdom says as "absolute" truth. Again, each technique should be reviewed on a case by case basis.

Solar CPV

Referring to Table 1, it would seem that MOVPE would be the obvious choice for the growth of thick concentrated photovoltaic (CPV) structures. However, Solar Junction has achieved a world-record for CPV solar cell efficiency using MBE [2]. Solar Junction's structure uses dilute nitride material for one of its junctions. Since the dilute nitride material can be grown lattice matched to GaAs, it does not have the reliability concerns associated with metamorphic materials used by many MOVPE competitors. MBE is the preferred technique for growing dilute nitride materials as it offers superior uniformity and composition control [3]. Furthermore, MBE is able to produces superior tunnel junctions (TJs) because it is better suited (as compared to MOVPE) to abrupt interface control and sharp doping profiles, particularly for thin layers. This allows MBE TJs to function without issue up to concentrations of >5000 suns without issue. This is a significant advantage for the Solar Junction material as it eliminates hot spots in the final device [4]. Hence CPV provides an example of how maintaining an open mind regarding "conventional wisdom" can result in an industry leading and enabling device technology.

COMMERCIAL CONSIDERATIONS

The three above examples are by no means exhaustive, nor was that the intent. It was simply an attempt to provide the reader a feeling for how technical performance of a given technique can be used in deciding which is "best." Equally important are the economic considerations as well as flexibility afforded by each.

From the commercial side, one key consideration regardless of the precise technical merit of a given epi growth technique is the cost profile for a given growth method. As noted in Table 1, the cost profiles for each technique are very different due to the specific utility/overhead requirements for each. For MOVPE, the overhead costs tend to scale with production volume. In contrast, for MBE the overhead is relatively fixed, and does not scale with volume. Therefore, MOVPE wins in a situation of significant overcapacity (significant idle time), and the opposite is true for MBE which excels on a cost basis when fully loaded. Understanding these cost profile considerations is particularly powerful as it opens that door to certain hybrid approaches that might possibly utilize the best characteristics of each technique.

In terms of manufacturing uptime, the two techniques are very similar based on our experience as the IQE group. However, for MBE, the downtime is concentrated to multiple month periods where the reactor is down. With MOVPE maintenance is a much more frequent but less time consuming occurrence. This is simply a characteristic born out of the fact that MBE must be conducted in ultrahigh vacuum. The consequence of this is that long bake times are required each time the growth chamber must be brought to atmospheric pressure for repairs. In contrast, MOVPE does not require such significant bake times. Therefore, MOVPE is able to recover more quickly from equipment failures. For MBE, this means that significant improvements are needed for equipment reliability and mean-time-to-failure for it to remain competitive. The technical merits and performance of MBE material are competitive for specific applications as noted above. However, significant redundancy is required to mitigate commercial risk.

CONCLUSIONS

Unfortunately, it is not a simple matter to discern which epitaxial growth technique is better, MBE or MOVPE. Each has specific merits in specific device applications. In addition, the loading and flexibility of the product mix being designed for must be considered in order to make a prudent decision. It is precisely for this reason that the IQE group has a split fleet of MBE and MOVPE reactors such that these can be utilized to provide the low cost solution to the market.

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ACRONYMS

MBE: Molecular Beam Epitaxy
MOVPE: Metal-organic Vapor Phase Epitaxy
OMVPE: Organometallic Vapor Phase Epitaxy
MOCVD: Metal-organic Chemical Vapor Deposition
PHEMT: Pseudomorphic High Electron Mobility Transistor
HBT: Hetrojunction Bipolar Transistor
VCSEL: Vertical Cavity Surface Emitting Laser
UHV: Ultrahigh Vacuum
LPD: Light Point Defect
Vp: Pinch-off voltage
Rsh: Sheet Resistance
Beta: Gain
Rb: Base Sheet Resistance
CPV: Concentrated Photovoltaic
TJ: Tunnel Junction