# Reduction of Process Variation Through Automated Substrate Temperature Uniformity Mapping in Multi-Wafer MBE Systems

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**Abstract**

**Measurement and control of substrate temperature is critical to the reduction of process variation when manufacturing compound semiconductor epiwafers. It is well known that the temperature of the substrate during growth can have a significant influence on physical properties of the semiconductor epilayers and the performance and yield of devices manufactured from those epiwafers. In this paper, we describe the application of an automated temperature measurement and mapping tool used to reduce growth temperature variation when manufacturing PHEMT and HBT epiwafers in RFMD's MBE production facility. We present examples of detailed temperature maps across multi-wafer platens of GaAs wafers with discussion of several causes of temperature variation. We also present a method for reducing run-to-run variation through automated substrate temperature setpoint adjustments.**

## INTRODUCTION

Measurement and control of substrate temperature is critical to the reduction of process variation when manufacturing compound semiconductor epiwafers. It is well known that the temperature of the substrate during growth can have a significant influence on properties of the semiconductor epilayers, including electron and hole mobility, minority carrier lifetime, interface abruptness, surface roughness, dopant incorporation and activation, diffusion of dopants, layer thickness, alloy composition, and incorporation of undesirable impurities. Depending on the structures being grown, precise control of some subset of these effects is critical to achieving acceptable electronic or optoelectronic device performance and yield.

In this paper we discuss the integration of a commercially-available band edge thermometry (BET) system into multi-wafer production MBE systems. RFMD has recently developed a technique for using this temperature measurement system to create detailed temperature maps across an entire multi-wafer platen of GaAs wafers during manipulator rotation. The technique was further refined by the BET system manufacturer with modifications that enable automated collection and display of these temperature maps. This capability allows evaluation of temperature uniformity of all wafers in the platen within a matter of minutes. Based on qualitative observations of the pattern of non-uniformity, the root cause of the temperature variation can be deduced. Then the temperature uniformity across each wafer may be improved either through adjustments to the multi-zone manipulator heater or through modifications to hardware including wafer platens, wafer backing rings or the manipulator assembly.

In addition to creating wafer temperature maps for diagnostic purposes, we use band-edge thermometry during production runs as feedback for automatic adjustment of temperature setpoints during execution of the growth recipe. The application of this tool to our production processes enables the reduction of wafer-to-wafer variation as well as variation across each wafer.

## THE TEMPERATURE MEASUREMENT SYSTEM

Due to the temperature dependence of the semiconductor bandgap, the temperature of a wafer can be inferred from the band edge extrapolated from infra-red transmission spectroscopy data [1]. This technique is convenient for adaptation to a variety of MBE systems due to the opportunity to use the substrate heater filament as the infra-red light source, the need for only one optical viewport, insensitivity to angle of incidence between optical path and substrate, and relative insensitivity to viewport coating. In practice, we have found that the technique provides us with a means of measuring the temperature of a semi-insulating GaAs wafer in a variety of multi-wafer MBE systems with a reproducibility much higher than previously achieved through use of an infra-red pyrometer. Data discussed and presented in this paper was acquired using the k-Space BandiT™, a commercially-available band edge thermometry system manufactured by k-Space Associates, Inc. [2].

The photodiode array in the spectrometer of the BET system provides the capability to acquire over 100 temperature measurements during each platen revolution at a typical rotation rate of 20 RPM. The BandiT™ software can be configured such that the data acquisition rate is synchronized with a position sensor on the rotating substrate manipulator. Acquired data points are then indexed to the corresponding position along a circle of constant radial distance from platen center.

Figure 1 shows temperature data taken from 6” GaAs wafers in a 7x6” platen configuration. The platen contains a single wafer in the center encircled by six outer wafers. The BET system optics head was positioned such that the centers of the outer six wafers would pass through its line of sight during platen rotation. The graph contains data from three rotation cycles; therefore, the six wafers appear to give 18 temperature peaks. From the periodicity of fine details in the data, we can infer that any random noise in the measurement is contributing errors of well under 0.5 °C.

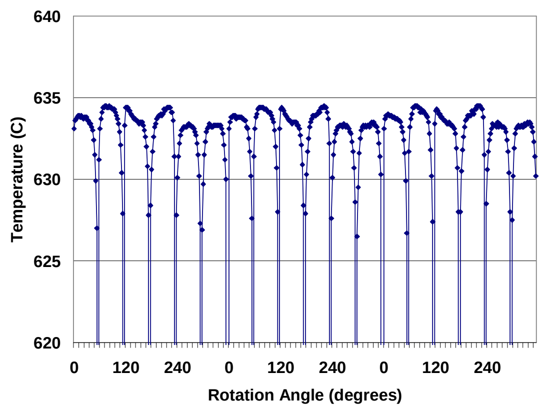


Figure 1: GaAs wafer temperature measurements during rotation of a platen of 6” GaAs wafers in 7x6” platen configuration. Data was collected from a circle ~6 inches from platen center.

By directing the BET system optics at a desired distance from platen center, then selecting the appropriate rotation angle of interest, one can monitor the temperature of one or more specific points on a wafer while the platen is rotating, therefore precisely tracking wafer temperature during growth of product wafers.

Alternatively, through successive adjustments of a micrometer on the tilt mount of the BET system optics, one can collect data from the rotating platen at many different radii and reassemble the data to form 2D temperature maps. As a manual technique, this is very tedious, but the value of such maps led RFMD to explore automation of the process. Following a collaborative development effort between RFMD and k-Space Associates, kSA has developed the hardware and software for automated 2D temperature mapping by adding a motorized tilt stage, new data acquisition modes and new graphical tools as available upgrade options to their BET product. Figure 2 shows an example of a surface plot of temperature data taken from the same 7x6” platen of GaAs wafers represented in Fig. 1.

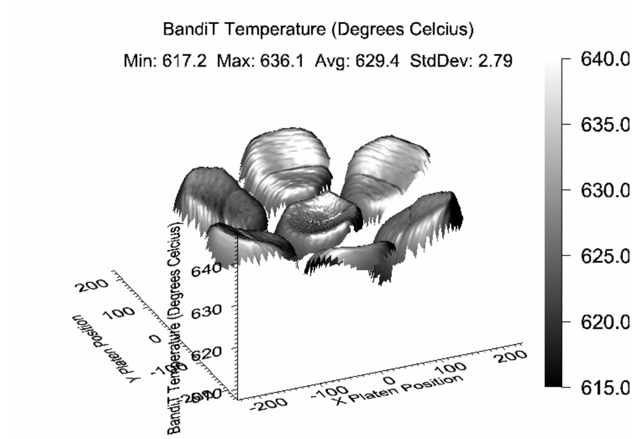


Figure 2: Surface plot displaying the measured GaAs wafer temperature distribution across the seven 6” wafers in a platen. Power supplied to the outer perimeter heat zone is 8% of applied manipulator heater power.

REDUCING TEMPERATURE NON-UNIFORMITIES

MBE systems sized to accommodate platens of multiple 6” wafers typically utilize manipulator heaters electrically isolated into multiple heat zones (e.g. central and outer temperature zones). The division of power between zones can be adjusted through the MBE control software with the goal of reducing temperature variation across a platen of wafers. Temperature uniformity maps such as those seen in Figs. 2 and 3 can be used as an aid in determining the optimum power distribution between the multiple zones.

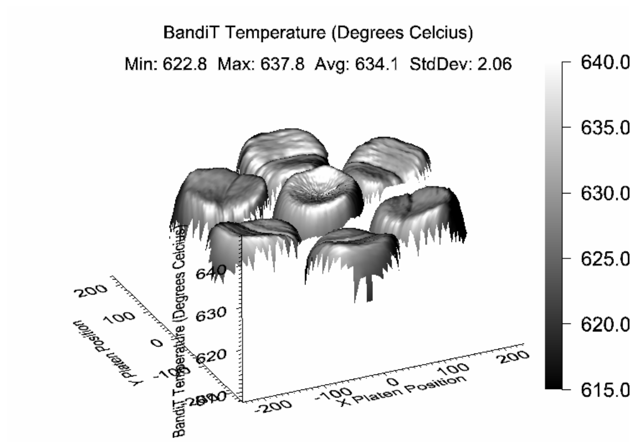


Figure 3: Surface plot displaying the measured GaAs wafer temperature distribution across the seven 6” wafers in a platen. Power supplied to the outer perimeter heat zone is 4.3% of applied manipulator heater power

The surface plot in Fig. 2 shows an 8 °C temperature difference between the center of the center wafer and the peak temperature near the outer edge of the outer wafers. After reducing the outer zone heater power from 8% to 4.3%

of total applied manipulator heater power, this temperature difference was reduced to 2 °C as shown by the data plotted in Fig. 3. Power ratio optimization using such temperature maps has become part of RFMD's standard MBE system setup procedure after any major maintenance of the growth chamber and/or cleaning of the platens.

Not all substrate temperature non-uniformity problems can be addressed with adjustments to manipulator heater zone power ratios. Note that Figs. 4 and 5 show temperature variation patterns with a strong component that has radial symmetry with respect to wafer centers.

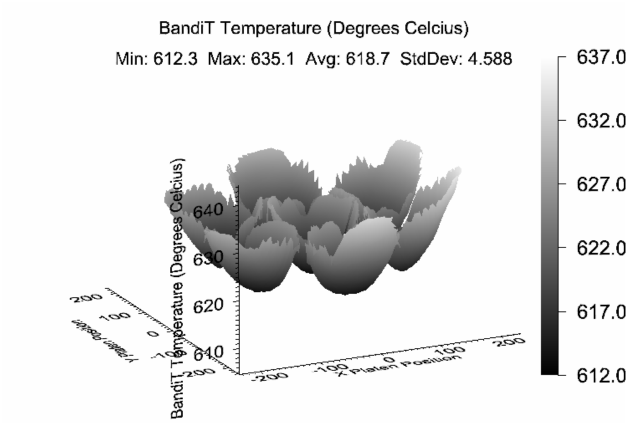


Figure 4: Surface map displaying the measured GaAs wafer temperature distribution across the seven 6" wafers in a platen. Increased contact area between wafer and platen is causing elevated temperatures at the wafer perimeters.

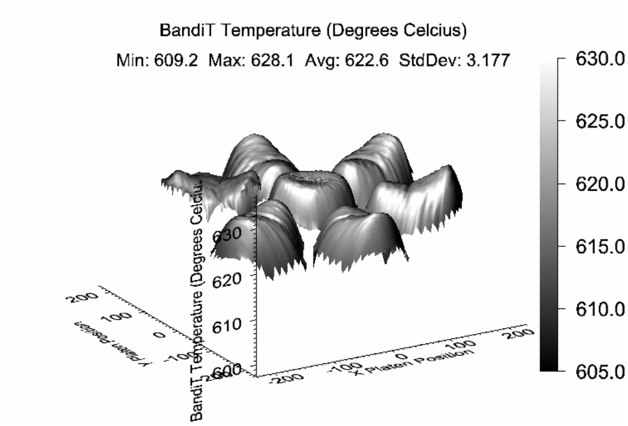


Figure 5: Surface map displaying the measured GaAs wafer temperature distribution across the seven 6" wafers in a platen. Same wafers and platen as in Fig. 4, but wider wafer backing rings cool the wafer perimeters.

Because the molybdenum or graphite platen is typically hotter than the radiatively heated GaAs wafers, heat is conducted from platen to wafer through the ledge that the wafer perimeters rest upon. An appropriately-sized wafer backing ring will act as a heat shield between the wafer perimeter and the heater filaments to reduce the temperature gradient between wafer perimeter and wafer center. Based on the observed symmetries in the data of Fig. 4, one would deduce that improved temperature uniformity could be achieved through use of either a wider backing ring or a reduced contact area between wafer and platen (narrower platen ledge). Figure 4 data was collected from a platen design that incorporates a wider ledge than that represented in Figs. 1-3, but same backing ring design. By contrast, the data plotted in Fig. 5 represents measurements from the same platen as Fig. 4, but with backing rings that are 1 mm wider (2 mm smaller inner diameter). As expected, the wider backing ring cools the perimeter of each wafer. It is apparent that the optimum ring width for this platen design is somewhere in between the two sizes used for these measurements.

When applying temperature uniformity mapping as a screening tool, we have observed other non-uniformity features that indicate warped or otherwise damaged platens that should be removed from production service. Furthermore, this data collection technique is extremely useful in studying many factors that influence wafer temperature uniformity. The results have been applied to the modification of MBE component designs to realize improved wafer temperature uniformity. A more detailed discussion will be presented elsewhere regarding various design elements affecting temperature uniformity in multi-wafer MBE systems.

## AUTOMATED TEMPERATURE ADJUSTMENTS

In addition to creating wafer temperature maps for diagnostic purposes, we use band-edge thermometry during production runs as feedback for automatic adjustment to temperature setpoints during execution of the growth recipe. In the absence of using feedback from wafer temperature measurements, we have found that run-to-run temperature variation within a single MBE reactor can be greater than 50 °C due to subtle differences between seemingly identical platens. For example, unintentional, small amounts of deposition on the heater-facing surface of a platen build up over time and change the platen emissivity. This changes the relative absorption or reflection of heat radiating from the manipulator heater.

Figure 6 shows an example of temperature data collected from 34 production growth runs spread over several days. The runs were distributed between ten different platens of 14x4" configuration. When applying the same manipulator thermocouple setpoint to each run, the resulting wafer temperatures varied by more than 50 °C and grouped strongly by platen identification number. The strong grouping by platen ID indicates that differences are likely due to variations in deposition on the platens.

Although we have not implemented real-time temperature control based on feedback from the BET system, we have added a feature to our MBE growth recipes such that the MBE control software will calculate an offset to the manipulator temperature setpoint during an early stage of the MBE growth recipe. This offset value is then uniformly applied to setpoints in all future recipe stages regardless of target temperature for each subsequent stage.

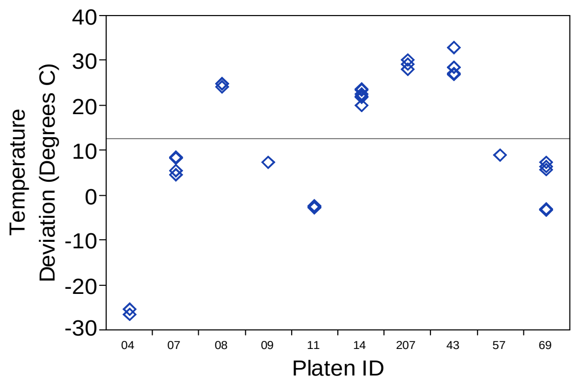


Figure 6: Oneway plot of measured temperature deviation from target. Data represents 34 MBE growth runs distributed between ten different platens of varying growth history. These temperature measurements were acquired early in each growth run prior to application of any corrective setpoint offsets.

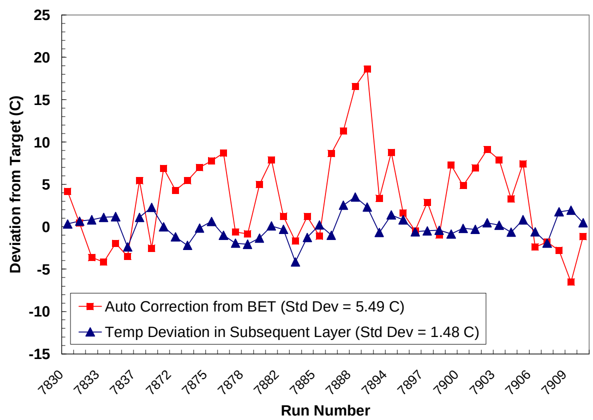


Figure 7: Trend chart showing automatic manipulator setpoint offset corrections and the resulting deviation from wafer temperature target in a subsequent layer. Data was collected from a series of 46 production epiwafer runs.

Figure 7 shows two trends calculated from BET measurements during growth of 46 sequential production runs. The squares represent the setpoint offset calculated from a wafer temperature measurement early in the growth recipe. The triangles represent the measured deviation from target temperature during growth of a subsequent layer approximately 35 minutes later in the recipe. Note that the run-to-run reproducibility of temperature has a standard deviation of 5.49 °C before application of the automatic setpoint correction, but a standard deviation of 1.48 °C for wafer temperatures measured after the setpoint correction has been applied. Thus we can insure a reproducible growth temperature for the active layers of the epitaxial structure in spite of minor unavoidable differences between platens holding those wafers.

## CONCLUSIONS

A uniform and reproducible substrate temperature during epitaxy is critical to maintaining tight control of the performance characteristics of electronic and optoelectronic devices fabricated from the resulting epiwafers. RFMD uses band edge thermometry to help insure reproducible growth conditions between a variety of different MBE growth systems and wafer sizes. Automated temperature measurements and setpoint adjustments are then applied within growth recipes to reduce run-to-run variation within individual MBE systems. Furthermore, growth temperature uniformity across each wafer and between wafers in a single run is optimized through use of data collected from a unique, automated substrate temperature mapping tool.

## ACKNOWLEDGEMENTS


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## ACRONYMS

BET: Band Edge Thermometry
HBT: Heterojunction Bipolar Transistor
MBE: Molecular Beam Epitaxy
PHEMT: Pseudomorphic High Electron Mobility Transistor