Measurement and thermal modeling of sapphire substrate temperature at III-Nitride MOVPE conditions

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Abstract

Growth rates and alloy composition of AlGaIn grown by MOVPE is often very temperature dependent due to the presence of gas-phase parasitic chemical processes. These processes make wafer temperature measurement highly important, but in fact such measurements are very difficult because of substrate transparency in the near-IR (~ 900 nm) where conventional pyrometers detect radiation. The transparency problem can be solved by using a mid-IR pyrometer operating at a wavelength (~ 7500 nm) where sapphire is opaque. We employ a mid-IR pyrometer to measure the sapphire wafer temperature and simultaneously a near-IR pyrometer to measure wafer pocket temperature, while varying reactor pressure in both a N_2 and H_2 ambient. Near $1300^\circ C$, as the reactor pressure is lowered from 300 Torr to 10 Torr the wafer temperature drops dramatically, and the ΔT between the pocket and wafer increases from $\sim 20^\circ C$ to $\sim 250^\circ C$. Without the mid-IR pyrometer the large wafer temperature change with pressure would not have been noted. In order to explain this behavior we have developed a quasi-2D thermal model that includes a proper accounting of the pressure-dependent thermal contact resistance, and also accounts for sapphire optical transmission. The model and experimental results demonstrate that at most growth conditions the majority of the heat is transported from the wafer pocket to the wafer via gas conduction, in the free molecular flow limit. In this limit gas conductivity is independent of gap size but first order in pressure, and can quantitatively explain results from 20-300 Torr. Further analysis yields a measure of the thermal accommodation coefficients; $\alpha(H_2) = 0.23$, $\alpha(N_2) = 0.50$, which are in the range typically measured.

Keywords: A3. Metalorganic vapor phase epitaxy; A3. Metalorganic chemical vapor deposition; A3. Organometallic vapor phase epitaxy; A1. Heat transfer; B1. Nitrides

1. Introduction

Parasitic chemical processes during III-Nitride MOVPE often create a strongly temperature dependent film deposition rate [1-15], which makes temperature measurement critical for control of film thickness and alloy composition. Unfortunately, the visible and near-IR transparency of the substrates typically used (sapphire, GaN, AlN, SiC) prevents the use of conventional pyrometry to directly measure substrate temperatures. These approaches actually measure the wafer carrier, or wafer pocket temperature, and are thus only an indirect proxy of the true wafer temperature. Alternative pyrometric methods based on GaN opacity at $\sim 400\text{nm}$ and sapphire opacity in the mid-IR ($\sim 7500\text{ nm}$) have the ability to directly measure the true wafer temperature [16-18], but widespread adoption of these tools has not yet occurred. We also note that the near-UV or $\sim 400\text{ nm}$ pyrometer is not viable unless an absorbing layer of GaN is present, which is not typically the case when growing AlN or high Al-content AlGaIn layers for UV-emitters or power electronic applications, leaving the mid-IR pyrometer as the only option.

Despite their disadvantages indirect temperature measurement methods are still most often employed because of their ease of use. One widely used indirect method is near-IR pyrometry with some type of emissivity correction added to account for changes in film transmission (via a reflection measurement) [19, 20]. Unfortunately the temperature offset between the wafer and wafer pocket is dependent on many MOVPE process variables (pressure, flow rate, gas composition), thus making the indirect methods less reliable. One noticeable example occurs during the MOVPE of AlN (and high Al content AlGaIn), which is often grown at lower total pressures (e.g. $< 100\text{ Torr}$) in order to minimize gas-phase parasitic chemical reactions. The effective thermal contact resistance between the wafer and substrate becomes very pressure dependent at these conditions, and temperature differences between the carrier and wafer, $\Delta T = (T_{\text{carrier}} - T_{\text{wafer}})$, can be greater than 100°C [16]. If only an indirect method is used this wafer temperature change would not be seen, and any change in growth rate, composition, etc. might be erroneously ascribed to a pressure change alone.

To study this effect in more detail we have used a mid-IR pyrometer to directly measure the sapphire wafer temperature, near 1300°C, in a N₂ and H₂ ambient, at pressures in the 10-300 Torr range. The susceptor temperature was also measured with a conventional near-IR pyrometer, to yield accurate ΔT values. In order to explain the experimental observations we have developed a quasi-2D thermal model that includes a proper accounting of the pressure-dependent thermal contact resistance. The model also includes radiative heat exchange using the gray body approximation, with an extension to include the effect of sapphire transmission. One future goal of this work would be to generate a model with sufficient accuracy to serve as a supplement to the indirect methods, when no absolute temperature measurement method is available.

2. Experimental Procedure and Results

The experiments were performed in a custom single 2-inch wafer (2") reactor using a design provided by North Carolina State University [21-23]. The general reactor design is similar to our earlier rotating disk reactors (RDR's), with vertical gas injection from the top impinging on a wafer perpendicular to the gas stream [1,24-26], although details of the gas injection and wafer loading are now somewhat different. The addition of a 30 kW RF generator and low emissivity TaC-coated graphite susceptor enables the system to reach temperatures of $\sim 1600^{\circ}\text{C}$, with our aim to explore high temperature AlN and AlGaIn MOVPE. In this study rotation rates were kept at or below ~ 200 rpm, which is too low to exert any significant influence on the gas flow, but high enough to help smooth out any temperature irregularities due to RF coupling variations.

Temperatures were measured with two types of pyrometers. A standard near-IR (~ 900 nm) pyrometer (IRCON 5R-1810100, operated in single color mode) was used to measure the TaC-coated susceptor temperature, normally looking at the center of the wafer pocket. Even with a sapphire wafer in place, this pyrometer only observes the radiation emitted from the susceptor, as the wafer remains transparent (no significant absorption) in the near-IR even at very high temperatures [27]. After accounting for wafer transmission losses solely due to reflection, the susceptor temperature in the wafer pocket can be accurately measured. A second, mid-IR (~ 7500 nm) pyrometer was used to measure the sapphire wafer temperature, as has been described in more detail previously [17]. At this wavelength sapphire is opaque, so it is possible to measure temperature radiometrically. Using these two pyrometers allows simultaneous measurement of both the wafer pocket and sapphire wafer temperatures.

Typically there will be a temperature difference (offset) between the pocket and wafer, and this offset is potentially dependent upon reactor conditions (pressure, gas-composition, flow rate, etc.). Changes in reactor pressure are particularly significant, as shown in Fig. 1; one set of curves is for pure N_2 and the other pure H_2 . At higher pressures (>100 Torr) the offset is typically $10\text{-}30^{\circ}\text{C}$, and nearly

independent of pressure, but as the pressure is lowered below 100 Torr the sapphire temperature begins to drop precipitously, while the wafer pocket temperature actually increases slightly (RF power held constant). At 10 Torr the offsets are 253°C (H₂) and 294°C (N₂). Without the mid-IR pyrometer these large temperature changes in the 10-100 Torr pressure range would not be apparent, and therefore variations in AlN or AlGaIn growth rate and/or material properties (e.g. alloy composition, impurity concentrations, etc.) could be erroneously assigned to pressure changes alone. A similar trend with pressure was observed previously using a 400 nm pyrometer for GaN-coated sapphire, but not quantitatively explained [16].

3. Thermal Model Description and Results

The behavior of the temperature offset seen in Fig. 1 is thought to arise from the thermal contact resistance (or a portion of it) being pressure dependent, an effect that has been studied in many physical systems [28, 29]. The physical basis of this observation is that when the mean free path (Λ) becomes comparable to or larger than the distance (d) between two surfaces ($Kn = \Lambda/d > 1$), heat exchange via gas conductivity no longer follows the behavior in the continuum limit. As a point of reference $\Lambda(N_2)$ is ~20 microns at 1000°C and 10 Torr, and the gap size is typically a few microns (in the absence of significant wafer bow). In the continuum limit the heat flux (q) is nearly independent of pressure and inversely proportional to distance. In contrast, in the free molecular flow regime q_{molf} is first order in pressure and independent of distance, obeying equation 3.1 [ref 30 eqn. 1.136].

$$q_{molf} = \frac{\alpha}{8} \left(\frac{\gamma+1}{\gamma-1} \right) \frac{P \cdot v}{T} \Delta T \quad (3.1)$$

Here α is an effective thermal accommodation coefficient (vide infra), $\gamma = C_p/C_v$ (heat capacity at constant pressure/heat capacity at constant volume; typically ≈ 1.4 for diatomic gases), and v = average molecular velocity.

This heat flow mechanism is in fact very important for most cold-wall MOVPE environments, and as we will see is often the dominant path by which heat flows from the susceptor (or any wafer carrier) to the wafer. In addition to q_{molf} , there are potentially two parallel pathways for heat flow; radiation exchange (q_{1rad}) and conduction through solid points of contact. We find no evidence the latter plays a role so it is not included in the following discussion. As a point of reference for the remainder of the discussion, refer to the equivalent thermal circuit diagram; Fig. 2. The two terms just described; q_{molf} and q_{1rad} represent the heat flux flowing through R_{molf} and R_{1rad} , respectively, and represent heat flow from the susceptor wafer pocket (node 1 at temperature T_1) to the sapphire wafer (node 2 at temperature T_2). The third node is the reactor wall, and heat flowing from the wafer to the reactor wall occurs via emitted radiation (q_{2rad}) and gas convection/conduction (combined into one term; q_{gas}).

In this study we have made a simplifying approximation in regard to the wafer itself; we are ignoring the temperature gradient through the wafer, and treating it as if it had zero thickness. At the power densities of interest ($\sim 10 \text{ W/cm}^2$) the temperature gradient across a standard 430 micron thick sapphire wafer is about 5°C , which is relatively small compared to the temperature gradients of interest (10's to 100's of degrees). Furthermore, this small gradient does not change appreciably when we are examining the effect of pressure at constant RF power, so it only introduces a small offset.

One property of the sapphire that requires special note is that it is transparent from the UV to the mid-IR, even at very high temperatures ($>1200^\circ\text{C}$) [27, 31]. The sapphire absorption edge in the mid-IR blue-shifts with increasing temperature; going from $\sim 5000 \text{ nm}$ at room temperature to $\sim 4000 \text{ nm}$ at 1400°C . For a black-body (or gray body) at temperatures above $\sim 700^\circ\text{C}$ more than 50% of the total radiative power is in the band below 4000 nm [32]. Therefore the effect of sapphire transmission on radiative coupling is very significant; a large fraction of radiation from the susceptor simply passes through the sapphire wafer without absorption. For simplicity we will model this effect using the gray body approximation, extended to include sapphire transmission.

An analysis of the radiative fluxes between two surfaces, with one material being semitransparent ($0 < \tau < 1$) is shown in Fig. 3; using the gray-body approximation framework [32]. The surfaces are assumed to be semi-infinite, and multiple reflections/transmissions are summed using the $1 + x + x^2 + x^3 + \dots = \frac{1}{1-x}$ identity. Six terms are derived, corresponding to the fluxes emitted (q_{emit}), reflected (q_{refl}) and transmitted (q_{trans}) for each surface. The four fluxes for emission and reflection are used to define the net radiative flux (q_{1rad}) flowing from **1** to **2**, which is given by Eqn. 3.2 (σ = Stefan-Boltzmann constant, ϵ_1 = emissivity of **1**, etc.). The two transmitted fluxes are summed to define q_{trans} , as shown in Eqn. 3.3. Note when $\tau_2 = 0$ eqn. 3.2 reduces to the standard expression for two non-transparent surfaces [32], and eqn. 3.3 = 0. The remaining radiation flux is that emitted from **2** towards the reactor wall (q_{2rad}), and is given in Eqn. 3.4. Finally, the expression for q_{gas} is given by eqn. 3.5, where R_{gas} may have contributions from both convective and conductive heat transfer.

$$q_{1rad} = q_{1emit} - q_{1refl} - q_{2emit} + q_{1refl} = \sigma \frac{\epsilon_1(\epsilon_2 + \tau_2)T_1^4 - \epsilon_1\epsilon_2T_2^4}{1 - R_1R_2} \quad (3.2)$$

$$q_{trans} = q_{1trans} + q_{2trans} = \sigma \frac{\epsilon_1\tau_2T_1^4 + \epsilon_2R_1\tau_2T_2^4}{1 - R_1R_2} \quad (3.3)$$

$$q_{2rad} = \sigma\epsilon_2(T_2^4 - T_w^4) \quad (3.4)$$

$$q_{gas} = \frac{T_2 - T_w}{R_{gas}} \quad (3.5)$$

These five heat flux terms (Eqns. 3.1-3.5) are then used in two equations defining the total heat flux flowing through the sapphire wafer (ρ_{waf}). Heat flow between the susceptor and wafer is given by Eqn. 3.6, and heat flow between the wafer and reactor wall is given by Eqn. 3.7.

$$\rho_{waf} = q_{1rad} + q_{molf} \quad (3.6)$$

$$\rho_{waf} = q_{2rad} + q_{trans} + q_{gas} \quad (3.7)$$

At this point, if ρ_{waf} is a constant and all other physical properties are defined, we can solve the non-linear Eqns. 3.6 and 3.7 to yield T_1 and T_2 . In fact, using this boundary condition ($\rho_{waf} = \text{constant}$) yields unsatisfactory results; as R_{molf} is increased (equivalent to lowering the pressure) T_1 increases much more than is observed experimentally, while T_2 only drops slightly. If we use a constant T_1 boundary condition we can recover a large drop in T_2 as the pressure is lowered (as observed experimentally), but we lose the small increase in T_1 .

We were able to make a substantial improvement in behavior by making the model “quasi-2D”. The susceptor is divided into two sections; one section is the wafer pocket with the wafer in place, while the second larger section is simply the remainder of the susceptor. The heat flux through the remainder of the susceptor (ρ_{ros}) is given by Eqn. 3.8. The susceptor is assumed to be isothermal, but ρ_{waf} and ρ_{ros} are not necessarily equal. In this case the total power (P_{total}) is given by Eqn. 3.9, and this value is held fixed as a boundary condition. This segmentation allows some power redistribution to occur in response to changes in reactor conditions, and greatly improves the behavior of the model.

$$\rho_{ros} = \sigma \frac{\varepsilon_1 \varepsilon_w (T_1^4 - T_w^4)}{\varepsilon_1 + \varepsilon_w - \varepsilon_1 \varepsilon_w} + \frac{T_1 - T_{wal}}{R_{gas}} \quad (3.8)$$

$$P_{total} = A_{waf} \cdot \rho_{waf} + A_{ros} \cdot \rho_{ros} \quad (3.9)$$

A_{waf} = wafer area, A_{ros} = remainder of susceptor area

The wafer area is known (20.3 cm^2), and we compute the area the rest of the susceptor using the known dimensions of the main cylindrical section (7.62 cm diameter X 3.18 cm height), but not including the 1.27 cm diameter supporting shaft. Since a portion of the support shaft does get hot this approximation tends to underestimate the surface area by a small amount. Defining P_{total} is not without some difficulty; we know the total RF power generated but not all of it is absorbed by the susceptor. A series of baseline tests were done in the power range of interest without the susceptor in place, and it

was found that $\sim 50 \pm 5\%$ of the RF power (P_{RF}) is in fact dissipated elsewhere. Therefore the power absorbed is given by $P_{\text{total}} = 0.5 \times P_{\text{RF}}$.

To solve the model equations we also need values for four optical properties (ϵ_1 , ϵ_2 , τ_2 , and ϵ_w), along with estimates of R_{gas} and the thermal accommodation coefficient (α). At high temperatures (1100-2000°C) the total hemispherical emissivity of TaC (ϵ_1) is in the range of 0.4-0.5 [ref 31, data table 299], and we chose an average value of 0.45. Choosing appropriate values of ϵ and τ for sapphire is more difficult, as a great deal of the tabulated values are for polycrystalline alumina of varying purity and crystal grain size. Above 1100°C most values for alumina are in the 0.3-0.5 range [ref 31, figure 48A, and 59], with the expectation that high purity crystalline sapphire would be in the lower end of this range. We therefore chose $\epsilon_2 = 0.35$. This ϵ value, and an average 2-surface reflectance value of 0.15 fixes a value of $\tau_2 = 0.5$ ($\tau_2 = 1 - \epsilon_2 - R_2$). Determining an appropriate value of the wall emissivity also requires some level of approximation, given its geometry and complexity (the reactor wall is predominately fused silica; concentric tubes with water in the gap for cooling, but the gas injector is entirely stainless steel). The radiative component in Eqn. 3.8 is written to allow for some back-reflection of radiation from the susceptor when $\epsilon_w < 1$, and currently we are essentially treating ϵ_w as an adjustable parameter to control the magnitude of this effect. One rationale for doing this is when we use our best guesses for P_{total} and all the other physical properties, the computed susceptor temperature (with $\epsilon_w = 1$) is typically 50-100°C lower than the measured value (in the 1300°C range). Of course it is possible we have underestimated P_{total} , and/or overestimated ϵ_1 , but by allowing for some degree of radiative back-reflection ($\epsilon_w < 1$) we can raise the calculated temperature to match the experimental measurement using $\epsilon_w \sim 0.8$.

To estimate the values of R_{gas} a 2D model of fluid flow and heat transfer in the reactor was solved using the Ansys Fluent software [33]. Geometrical features of the reactor were used, with a fixed outer-wall temperature boundary condition of 100°C and disk temperature of 1300°C. The model calculates the temperature and velocity fields as gas enters the reactor, flows across the heated (and rotating at 200

rpm) susceptor and exits the reactor. Calculations were performed over the pressure range 10 – 300 Torr for H₂ and for N₂ gases at 13 slm. The flow simulations yield the gas heat transfer coefficient averaged over all surfaces of the susceptor. As expected this coefficient has almost no dependence on pressure.

After specifying all of the parameters discussed above, the remaining unknown is the thermal accommodation coefficient (α). This is in fact the value we hope to extract from the measured temperature offsets (ΔT) with the aid of the thermal model (assuming the structure of the model is valid). There are many ways of doing this, and we chose the following method. With all input values set except R_{molf} , we used the model to generate a ΔT_{model} vs R_{molf} “calibration” curve. For each experimental ΔT value we determine the corresponding R_{molf} value, and this in turn is plotted against the corresponding pressure. Results for N₂ and H₂ are shown in Fig. 4.

The log-log plot in Fig. 4 demonstrates that R_{molf} scales nearly perfectly as $1/P$, in accordance with eqn. 3.1. There is some departure from this scaling relationship below ~20 Torr, which will be discussed below. The fits to the data (for $P \geq 20$ Torr) using a β/P function can be used to determine that $\alpha(\text{N}_2) = 0.33$ and $\alpha(\text{H}_2) = 0.13$. The α values are actually a composite of the thermal accommodation coefficients for the two surfaces that the gas is exchanging energy with, α_1 and α_2 , as given by Eqn. 3.10 [ref 30, eqn. 1.137].

$$\alpha = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + 1} \quad (3.10)$$

If we assume $\alpha_1 = \alpha_2$, then $\alpha_1(\text{N}_2) = 0.50$ and $\alpha_1(\text{H}_2) = 0.23$. These values are in the range typically observed [ref 30, table 1.13], and demonstrate that on a per molecule-surface collision basis H₂ is actually less efficient (~0.4 X) than N₂ at exchanging energy with the two surfaces. However, since the collision rate for H₂ is $\sqrt{14}$ times higher than that for N₂, the net heat transfer rate for H₂ is 1.5 X higher.

Using the measured α values we can now directly compare the overall model predictions of ΔT as a function of pressure with the experimental observations, see Fig. 5. Note that the agreement between the model (solid) curves and experimental data (symbol) is good at pressures above 20 Torr. The disparity that arises below 20 Torr is simply another manifestation of the deviation seen in Fig. 4 at the lowest pressures. It appears that the root cause of this deviation is that as $\mathbf{R}_{\text{molf}} \rightarrow \infty$ ($P \rightarrow 0$) the temperature offset (ΔT) is asymptotically approaching the value defined by $\mathbf{R}_{\text{1rad}}$. For the optical constants used in the model this limiting $\Delta T_{P=0}$ value is $\sim 480^\circ\text{C}$, while the experimental curves appear to converge to a $\Delta T_{P=0} \sim 650^\circ\text{C}$. For comparison, if we set $\tau_2 = 0$ the model extrapolates to an even lower $\Delta T_{P=0} \sim 350^\circ\text{C}$, so the addition of the transmission component (with $\tau_2=0.5$) does improve model performance. Increasing the transmission value (τ_2) above 0.5 also tends to give better agreement (i.e. increases $\Delta T_{P=0}$), but we cannot achieve an exact fit using optical parameters we can currently justify, within the gray-body framework. In fact, we believe it is the large spectral mismatch between TaC and sapphire that is limiting the accuracy of the gray-body approximation. Sapphire only significantly emits (and absorbs) radiation at wavelengths longer than ~ 4 microns, while the emission for TaC is skewed towards shorter wavelengths; higher in the visible and lower in the infrared ($\epsilon = 0.6$ at 500 nm, $\epsilon = 0.2$ at 4000 nm). In the gray-body analysis emissivity is assumed to be constant at all wavelengths, so in material systems with large spectral differences it might not accurately describe the finer details of radiative transport. Currently, near 1300°C this error is only obvious below 20 Torr; at lower temperatures the error should be even smaller, but at higher temperatures it will be more of a problem. Improvements to the model will need to include some TaC and sapphire spectral information (go beyond the gray body approximation), and will be the subject of future work.

As a final point we examine the fraction of heat that is transferred from the susceptor to the wafer (and absorbed) via radiative transfer ($Fq_{1\text{rad}}$) and gas conduction ($Fq_{1\text{molf}}$), where $Fq_{1\text{molf}} = q_{1\text{molf}}/(\rho_{\text{waf}} - q_{1\text{trans}})$ and $Fq_{1\text{rad}} = 1 - Fq_{1\text{molf}}$. The transmission component that bypasses the wafer ($q_{1\text{trans}}$) is subtracted from the total head flow since this radiation was not absorbed. Trends for $Fq_{1\text{molf}}$ with

temperature and pressure are shown in Table 3.1. In all cases the majority of the heat is transported to the wafer by gas conduction in the small gap between the wafer and susceptor. As the temperature is raised this fraction falls and the fraction of heat carried by radiation increases; the trend is more obvious at lower pressure where R_{molf} is larger. The gray-body approximation discussed earlier will limit the accuracy of these values at high temperatures and low pressures, but the trends will hold true.

4. Summary

We have used a MIR pyrometer to measure the absolute sapphire wafer temperature near 1300°C, and found that it exhibits a large reactor pressure dependence. At constant RF power, when the pressure is lowered from 300 Torr to 10 Torr, the sapphire temperature drops ~250°C while the susceptor temperature rises ~25°C. The effect is larger in N₂ as compared to H₂. The temperature difference between susceptor and wafer (ΔT) scales approximately as 1/P, which suggests that heat conduction by the gas in the free molecular flow regime is the dominant heat transfer component. In the continuum limit gas conductivity is nearly independent of pressure, but gas filling the small gap between the wafer and susceptor transfers heat by a different mechanism, and the heat transfer rate is first order in pressure. In order to examine the issue quantitatively we built a simple “quasi-2D” model that includes the effect of sapphire transmission in the radiation exchange components. After using appropriate high temperature optical constants (ϵ , τ , R) for TaC and sapphire we have used the model to extract the heat transfer coefficient for the molecular flow component, and found that it well obeys the 1/P dependence from 20 to 300 Torr. The corresponding thermal accommodation coefficients (α) for N₂ and H₂ are measured and found to be; $\alpha_1(\text{N}_2) = 0.50$ and $\alpha_1(\text{H}_2) = 0.23$, which are in the expected range for these values. Hydrogen, as is normally observed, is actually a less efficient transporter of energy than N₂, on a per molecule-surface collision basis. But the much higher collision rate for H₂ compensates for this deficiency, and the overall heat transfer rate for H₂ is ~1.5 X that of N₂. In general, the vast majority of heat exchanged between the susceptor and the wafer occurs by the gas molecules,

with only a small fraction via radiation transfer. As the temperature is raised, and/or the pressure is lowered, the radiative component becomes more important, but is still $< 40\%$ for the conditions examined. A small disparity between the model and experiment arises when the pressure drops below 20 Torr, which is the region where the radiative component of heat exchange is becoming more evident. The disparity is likely due to inadequacies of the gray body approximation, given the large mismatch between the optical properties of TaC and sapphire. Future model improvements will need to go beyond the gray body approximation and include some spectral properties of the two materials.

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Table 3.1 Fraction of heat carried to wafer by gas conduction

Temperature(°C)	Fq_{1molf} (20 Torr N ₂)	Fq_{1molf} (200 Torr N ₂)
1000	0.87	0.98
1200	0.82	0.97
1400	0.75	0.96
1600	0.69	0.95

Figure 1 Temperature of as function of reactor pressure; sapphire wafer temperature - solid circles (red = H₂, blue = N₂), wafer pocket temperature – open squares (red = H₂, blue = N₂). Flow rate = 13 slm, and RF power absorbed = 2.5 kW. Solid and dashed lines are empirical fits.

Figure 2. Equivalent thermal circuit (1D); T_1 = susceptor temperature, T_2 = wafer temperature, T_w = wall temperature (see text for other term definitions)

Figure 3. Derivation of the radiation components for two infinite surfaces at T_1 and T_2 , with surface-1 being opaque; $R_1 = 1 - \epsilon_1$, and surface-2 being semi-transparent; $R_2 = 1 - \epsilon_2 - \tau_2$, $\tau_2 > 0$.

Figure 4. R_{molf} (deg-cm²-sec/ergs) versus Pressure for N_2 (blue-circles) and H_2 (red squares)

Figure 5. Comparison of model predictions (solid lines) with experimental values (symbols)