SVT Associates, Inc.

In-Situ 4000 White Paper

Solving the problems of pyrometry and thickness measurement during MBE and MOCVD.

Background

Pyrometry is a well established measurement technique and is successfully used in many applications. It has one main feature which makes it attractive for substrate temperature measurement during MBE or MOCVD: non-contact, vacuum compatible temperature sensing. However as those who have used pyrometry for semiconductor applications know, this technique is fraught with problems which greatly limit its usefulness. Some of those problems are listed in the table below.

SUBSTRATE TRANSPARENCY

Semiconductors by nature are partially transparent for wavelengths below the band gap which are usually in the infrared portion of the spectrum. This transparency causes two severe limitations in pyrometric measurements: low substrate emissivity and optical interference from other hot elements in the chamber.

BANDGAP SHIFTS.

The band gap of the semiconductor substrate is a strong function of temperature and so the basic assumption of constant emissivity made by standard pyrometers is not valid.

VIEWPORT COATING

Standard pyrometry computes temperature from the intensity of emitted radiation. If the viewport window through which the pyrometer measures the radiation becomes coated over time, the pyrometer temperature calibration will drift accordingly.

OBSCURATION ERRORS

This problem is similar to viewport coating in that there are errors introduced into the collection of radiated intensity by misalignment of the optics to the viewport window or other obscuration problems.

PICKUP OF STRAY LIGHT

Any hot surface in the chamber can radiate light. If that light makes its way into the pyrometer, the pyrometer will not be able to distinguish between "black body" radiation of the substrate itself and that of the stray light. Thus the stray light introduces an error into the measurement usually causing a higher than actual reading.

INTERFERENCE EFFECTS

When thin films having different index of refraction from the substrate are deposited, the resulting interference effects cause the radiated light to rise and fall with the film thickness even if the actual temperature is constant. This causes temperature measurement errors during film growth and can cause actual temperature fluctuations due to non-constant radiative cooling of the substrate.

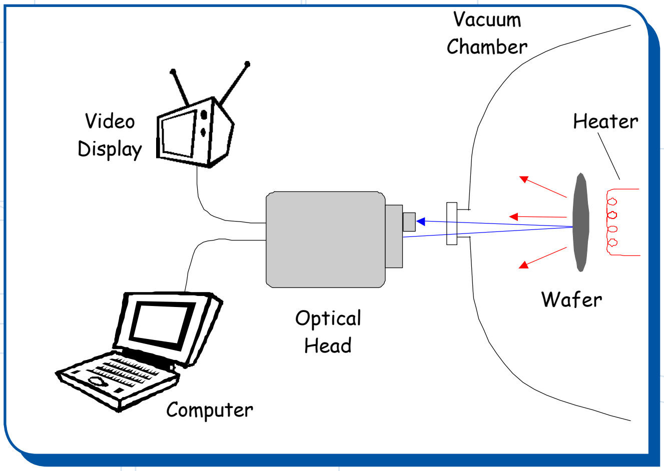
FILM ABSORPTION EFFECTS

If a narrow band semiconductor film (e.g. InAs) is deposited on a wider band substrate (e.g. GaAs) there is a strong change in the optical absorption and emission characteristics of the film/substrate system and often there is a corresponding real change in the temperature.

As a result of these problems, pyrometry has experienced only limited success in solving the critically important problem of accurate and repeatable substrate temperature measurement.

In-Situ 4000 Design Philosophy

SVT Associates has recognized these difficulties and has, in conjunction with our own MBE processing lab and UHV system and components expertise, designed a new pyrometer system which solves many of the problems preventing pyrometry from becoming an indispensable tool for both MBE and MOCVD processes. This system combines traditional pyrometry with specular reflectometry to provide a single instrument to monitor both substrate temperature and film thickness in real time.



The schematic diagram above shows the layout of the In-Situ 4000 system. The integrated optical head contains the reflectometer illumination source, computer communications interface, and a video camera for ease of aiming and alignment with the substrate.

SOLVING SUBSTRATE TRANSPARENCY

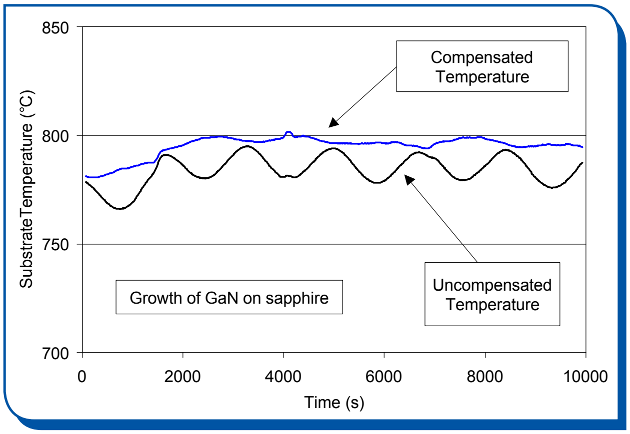
The problem of low emissivity and substrate transparency at infrared wavelengths is addressed by careful selection of the pyrometry wavelength. The In-Situ 4000 performs single wavelength pyrometry at 950 nm which is short enough to ensure that the substrate is opaque, and long enough to ensure a measurable optical radiation. Ensuring substrate opacity is a key element in addressing several of the previously listed difficulties. An opaque substrate prevents radiation from a filament heater from being transmitted though to the pyrometer. It also prevents other radiation sources in the chamber (effusion cells, ion gauge filaments, etc.) from scattering their light from the rough back side of the substrate into the pyrometer. Since optical absorption and radiation are closely coupled, substrate opacity ensures that the emissivity of the substrate is high enough to provide a measurable signal. Typical substrates such as silicon, GaAs and InP are sufficiently opaque at 950 nm for substrate temperatures typical of epitaxial growth.

SOLVING WINDOW COATING PROBLEMS

The problem of viewport window coating and optical alignment errors is addressed in the In-Situ 4000 through the use of "two color" or "ratio" pyrometry which measures optical radiation at two wavelengths and takes the ratio of the measured intensities. If the pyrometer is well designed and the film coating the viewport is spectrally neutral, then the temperature may still be calculated since these errors affect both channels equally. Since many of the viewport coating problems deal with "metallic" type films (e.g. Ga, In, As), these films attenuate the light equally between the two wavelengths, the ratio calculation is still valid. If the viewport becomes coated with a dielectric film causing interference effects, then the ratio measurement becomes imbalanced and may not be valid. The intensity ratio vs. substrate temperature will differ for varying substrate materials, so the In-Situ 4000 system allows the flexibility of a look-up table to translate from intensity ratio to reported temperature. This look-up table can be changed for different substrates, or updated to compensate for any calibration errors or instrument drift. The ratio pyrometry feature of the In-Situ 4000 provides the user with a repeatable day-to-day calibration which is independent of viewport coating effects.

SOLVING VARYING EMISSIVITY

The problem of unknown or shifting emissivity is solved using information from the accompanying reflectometer system. Under the conditions of an opaque substrate, a perfectly specular substrate front surface, and perfect uniformity of the deposited films, the emissivity may be measured via reflectometry at the same wavelength as the pyrometry. The relation linking emissivity, ε, and reflectometry, R, under these conditions is: $\varepsilon = 1 - R$. The In-Situ 4000 provides a 950 nm reflectometer which is matched to the 950 nm pyrometry system thus allowing this "emissivity compensation" to provide an emissivity independent temperature measurement. Thus, if the film being deposited has a index of refraction as the substrate producing interference effects, the reflectometry will observe these changes and the software will correct the error in the temperature calculation. The success of this technique depends upon how closely the materials system conform to the assumptions listed above, namely substrate opacity, surface specularity (smoothness), and film uniformity. If the substrate is not sufficiently opaque or the surface is rough and scatters significant amount of light, the $\varepsilon = 1 - R$ relation is no longer true. If the deposited film is not uniform, then the reflectance measurement (made at a single point on the substrate) may not be well correlated to the pyrometry measurement (made over a large area of the substrate).



The figure above shows the temperature error which can occur when depositing multilayer thin films. The graph shows the measured substrate temperature during the MBE growth of GaN on sapphire. The lower curve shows the temperature as measured using traditional pyrometry while the upper curve shows the temperature after compensation by the reflectometry system.

These new features of the In-Situ 4000 Process Monitor now allow accurate pyrometry to be performed in an MBE or MOCVD system.

In addition to accurate pyrometry, the reflectometer measures specular reflectance at two wavelengths: 950 nm and 470 nm. Reflectometry is obtained in real-time during deposition so that films which have differing index of refraction from the substrate produce reflectance oscillations in time. These reflectance oscillations can be analyzed in real-time to provide both film thickness and film index of refraction. The In-Situ 4000 has powerful analysis algorithms which can provide accurate growth rate, thickness, and index information. This valuable information can even be fed back to the growth system controller to achieve layer thickness precision improvements over traditional open-loop timed deposition control. The best growth rate and index of refraction measurements are obtained with films of at least $\lambda/4$ in thickness where λ is the reflectometer measurement wavelength (i.e. 950 nm or 470 nm).

The reflectometer uses two LEDs housed in the optical head to illuminate the wafer through the vacuum viewport window and detects the light with the same optical system as the pyrometry. Thus the system need only use a single, normal incidence viewport which is provided in many vacuum systems. The viewport must be large enough to allow room for both the illumination light to enter and the reflected and pyrometric radiated light to exit the chamber. The In-Situ 4000 requires a 2.75 inch Conflat viewport or larger to accomplish this measurement. Another requirement is that the viewport window be located at normal incidence to the substrate so that the illumination beam be specularly reflected back to the instrument. This places some limits on the substrate holders which need to maintain normal incidence alignment during use and especially during wafer rotation. The In-Situ 4000 system has special software features which can allow the measurement to function well even if the substrate tilts strongly during wafer rotation.

The In-Situ 4000 Process Monitor provides the MBE or MOCVD user with a complete tool for obtaining in real-time the two most important process parameters in film growth: temperature and thickness. The system uses only a single viewport window at normal incidence and is specifically designed for MBE and MOCVD processes.

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