SAND96-2198C

REAL TIME, *IN-SITU* TEMPERATURE MONITORING USING DIFFUSE REFLECTANCE SPECTROSCOPY

CONF-9609273--1

J.L.Booth, B.T. Beard
Thermionics Northwest, Inc.
231-B Otto St., Port Townsend, WA 98368

T.P.Pearsall, Z.Z. Wang
Department of Electrical Engineering
University of Washington, Seattle, WA 98185

J.E.Stevens, M.G.Blain, and T.L.Meisenheimer
Microelectronics Development Laboratory
Sandia National Laboratories
Albuquerque, NM 87185

RECEIVED
SEP 12 1996
OSTI

Real time temperature measurements have been performed on both GaAs and silicon substrates during wafer processing using a technique based upon diffuse reflectance spectroscopy (DRS). Good temperature resolution (±0.4°C) and rapid updates have enabled the process control potential of the device to be demonstrated.

Typically, the temperature of semiconductors is measured during processing with either thermocouples or using pyrometry. Unfortunately, these techniques have limitations and / or may be inaccurate. Pyrometry, for example, has several drawbacks. First, accurate temperature measurements require that the emissivity of the substrate be known *a priori*, and relies on a knowledge of how the emissivity varies during processing. In addition, the technique is susceptible to the presence of other light sources in the processing environment, such as heater radiation, plasma emissions, fluorescence, and so on. Finally, the useful temperature range for pyrometry is limited to above roughly 400°C for most commercial systems. This limitation is due, in part, to the characteristics of semiconductors. Semiconductors are transparent to photons with energy below the band gap of the material, and absorbing above this energy. The result is that the pyrometer must monitor the emission of the semiconductor at wavelengths where the substrate is opaque so as not to confuse the heater signal with the substrate signal. Unfortunately, thermal emission in this wavelength region decreases rapidly as the temperature decreases, until the signal is too low to perform useful measurements.

Thermocouples provide a simple, inexpensive alternative to pyrometry. However, the thermocouple must make good mechanical contact with the wafer to provide accurate temperature readings. In many applications, it is undesirable or even impossible to attach a device to the wafer. Further, the sample environment may contain corrosive gases, the sample may be rotating, and so on.

One solution to the temperature measurement problem is suggested by the optical properties of semiconductors. In general, semiconductors are transparent to light with energy lower than the band gap of the material, and opaque to radiation with greater energy. The result is that semiconductors display a characteristic step-like absorption edge. Being related to the temperature-dependent band gap of the material makes the optical absorption edge a candidate for thermometry. This idea was first proposed and demonstrated by Hellman and Harris [1] in 1986. These researchers used the heater radiation transmitted through a gallium arsenide (GaAs) wafer to characterize the temperature of the substrate.

DIFFUSE REFLECTANCE SPECTROSCOPY

This so-called band edge absorption temperature measurement technique was refined in 1991 by Tiedje *et al.* [2, 3, 4, 5]. Their technique is based upon diffuse reflectance spectroscopy and is the technique which is employed by the temperature measurement device described here. Instead of relying on the heater radiation as the light source, an external broadband lamp is used to illuminate the front of the wafer. Some of the light is specularly reflected from the surface of the sample,

HH

DISCLAIMER

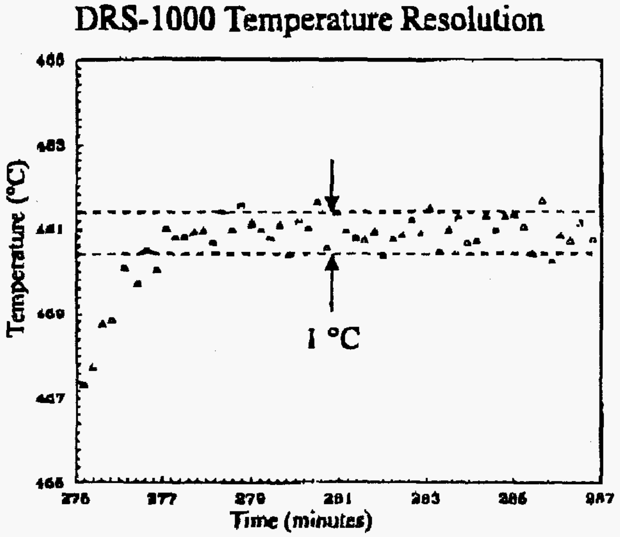

Figure 3. Typical temperature measurements obtained from a 450 micron thick semi-insulating GaAs wafer.

During the course of these studies a comparison was made between the DRS substrate temperature readings and the readings from the thermocouple used to control the power to the sample heater. The heater thermocouple is located between the heater and the sample inside the CBE reactor. It is used as the sensor for a feedback loop that controls the heater output. As can be seen in figure 4 there is a large discrepancy between the DRS substrate readings and the thermocouple readings. The heater thermocouple does not accurately reflect, either in magnitude or in temporal response, the behavior of the substrate. The substrate temperature has been observed to drift by as much as 15°C over a one hour period while the heater thermocouple readings remained constant.

In order to take advantage of these findings, the prototype system at the University of Washington was modified to convert the DRS sensor into a control device [7]. This was achieved by building an output circuit into the system that provided the voltage that would appear across a thermocouple junction at the temperature of the DRS reading. This voltage replaced the heater thermocouple in the heater control loop and, with appropriate tuning of the P.I.D. settings, direct substrate temperature control has been demonstrated [7]. Under DRS control the observed equilibration times were of the order of ten minutes over the range of temperatures tested (25°C - 600°C), compared to more than an hour for some cases under the usual heater thermocouple control. As well, the observed temperature drifts were for some cases under the usual heater thermocouple less than ±1°C. Control and monitoring of substrate in MBE/CBE applications continues to be an active area of research.

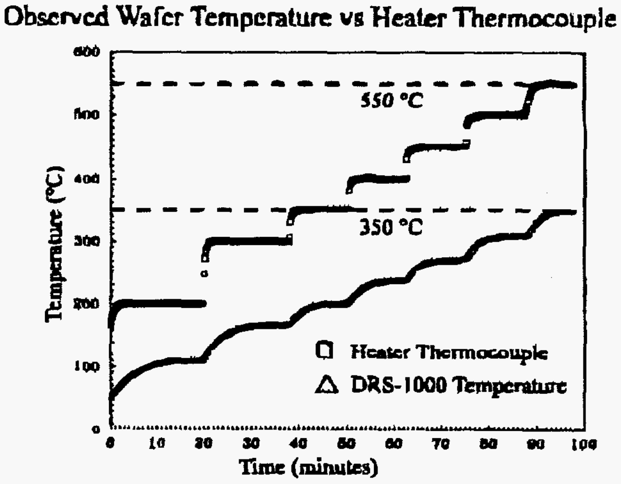

Figure 4. Comparison of DRS substrate temperature measurements and heater control thermocouple readings. As is evident, the heater thermocouple does not accurately reflect the behavior of the substrate.

SILICON ETCHING

In collaboration with J. E. Stevens, M. G. Blain, and T. L. Meisenheimer of the Microelectronics Development Laboratory at Sandia National Laboratories, a study of DRS temperature monitoring of silicon wafers during chemical downstream etching was carried out [8].

The chemical downstream etch system was modified by replacing the top plate of the etch chamber with an eight inch diameter quartz viewport. The DRS system was situated above the viewport allowing a 1 cm diameter area of the silicon wafer to be sampled for each reading. A variety of 200 mm diameter silicon wafers were loaded in to the chamber and electrostatically clamped to the temperature regulated chuck. Two typical temperature versus time traces are shown in figure 5 for two different patterned silicon wafers. Each wafer entered the processing chamber at room temperature (25°C). As they were placed in contact with the chuck, their temperature rose abruptly until they came into equilibrium with the chuck. During the exothermic etch process the substrate temperature was observed to rise to a new equilibrium temperature and then drop back down to the chuck temperature once the etch was halted. The difference between the two traces is that in one case the wafer was not electrostatically clamped to the chuck while in the other the wafer was. As expected, when the wafer was not clamped the poorer thermal contact resulted in a larger temperature rise during the etch process.

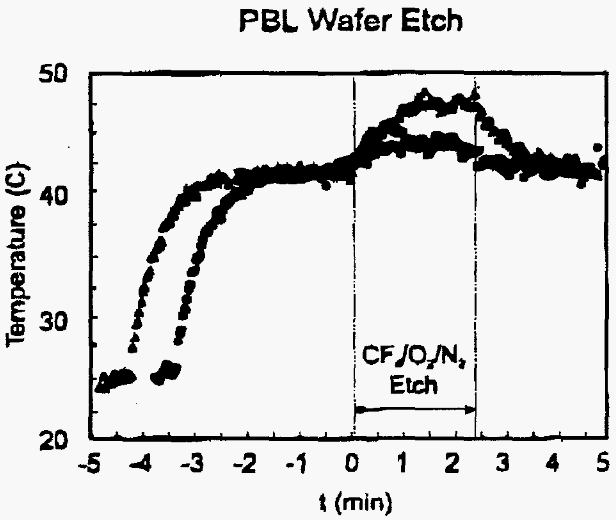

Figure 5. Temperature response of a patterned PBL silicon wafer. As the wafer is placed on the temperature regulated chuck its temperature rises until it comes into thermal equilibrium. A second, smaller temperature rise accompanies the exothermic etch process. The effect of clamping the wafer to the chuck is demonstrated by a smaller temperature increase during the etch process.

The observed increase in substrate temperature also reflected the gas mixture used for etching. Using a $CF_4/O_2/N_2$ mixture resulted in a (3.0 ±.5)°C temperature rise compared to a (9.2 ± 0.9)°C for the more aggressive NF_3 etch chemistry. Following reference [9], the observed temperature rise and the observed thermal time constant can be related to the etch rate of the silicon substrate. Using a post-processing knowledge of the amount of material etched for each process, the temperature rise expected for each gas chemistry can be calculated. The predictions, $\Delta T = (3.4 \pm 0.2)$°C for a $CF_4/O_2/N_2$ gas mixture and $\Delta T = (9.0 \pm 0.4)$°C for an NF_3 gas chemistry, agree very well with the observations. This indicates that, with appropriate calibration, the amount of material etched as a function of time can be determined in real time. Again, the DRS technique has the potential for use as a monitor and as a control device for this application.

CONCLUSION

Diffuse reflectance spectroscopy is a promising tool for *in-situ*, real time substrate temperature monitoring. It has the advantages of operating over a wide temperature range and on many applications, it is readily adaptable to existing devices, and offers rapid update speeds and good temperature resolution. The potential of the device for process control has been demonstrated and future work is planned in this direction.

REFERENCES

[1] E.S. Hellman and J.S. Harris, Jr., J. Crystal Growth 81, 38 (1986).
[2] M. K. Weilmeier, K. M. Colbow, T. Tiedje, T. Van Buren, and Li Xu, Can. J. Phys. 69, 422 (1991).
[3] C. Lavoie, S. R. Johnson, J. A. Mackenzie, T. Tiedje, and T. Van Buren, J. Vac. Sci. Technol. A 10, 930 (1992)
[4] S. R. Johnson, C. Lavoie, T. Tiedje, and J. A. Mackenzie, J. Vac. Soc. Technol. B 11, 1007 (1993).
[5] S. R. Johnson, C. Lavoie, E. Nodwell, M. K. Nissen, T. Tiedje, J. A. Mackenzie, J. Vac Soc. Technol. B 12, 1225 (1994).
[6] T. P. Pearsall, S. R. Saban, J. L. Booth, B. T. Beard, and S. R. Johnson, Rev. Sci. Instrum. 66, 4977 (1995).
[7] Z. Z. Wang, T. P. Pearsall, B. T. Beard, and J. L. Booth, in preparation.
[8] J. L. Booth, B. T. Beard, J. E. Stevens, M. G. Blain, and T. L. Meisenheimer, to be published in J. Vac. Sci. Technol. A, Aug. 1996.
[9] S. A. Shivashankar and B. Robinson, J. Vac. Sci. Technol. A 4, 1826 (1986).

ACKNOWLEDGEMENTS

Part of this work done in collaboration with Sandia National Laboratories was supported by DOE Contract No. DE-AC04-94AL85000.