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TEMPERATURE MEASUREMENT OF METALLIZED SILICON WAFERS BY INFRARED TRANSMISSION USING SINGLE- AND DOUBLE-PASS GEOMETRIES

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ABSTRACT

The infrared transmission technique for the measurement of silicon wafer temperature has been extended to metallized wafers. For wafers with partial metal coverage, a single-pass method has been demonstrated from 200°C to 550°C. For wafers with blanket metal coverage, a novel double-pass infrared transmission technique is presented.

INTRODUCTION

The accurate measurement of the temperature of a silicon wafer is an important issue for integrated circuit processing. This is especially difficult in a Rapid Thermal Processing (RTP) environment. Pyrometry, for example, is difficult at low temperatures (<800°C), because the wafer emissivity depends on wafer temperature and because of the interference from the heating lamps. Thermocouples, another alternative, cannot be feasibly attached to every wafer, because of practical and contamination reasons. Recently, measurement of the absorption of infrared light has been used to measure the temperature of bare silicon substrate in an RTP reactor from 500-800°C [1,2]. Since the absorption of infrared light in silicon is a strong function of temperature, one can infer the temperature of the silicon substrate from the ratio of light transmitted at a higher temperature to that at room temperature. In an earlier paper, it was shown that the upper limit for the method of temperature measurement by infrared transmission in silicon is ~800°C [3]. At this temperature, the absorption of light at 1.55μm, which is the wavelength with the minimum absorption at high temperature, decreases to the point where there is no transmitted signal left to detect for reasonable (~mW) probe beams. Therefore, we were motivated to study applications involving metallization and silicides, since processing steps involving them generally occur under 800°C (as low as 200°C for palladium silicide formation). In this paper, the process of temperature measurement by infrared transmission has been extended to a lower temperature range, by using shorter wavelengths of infrared light, and to wafers with varying degrees of metal coverage. A new double-pass version of the technique is also presented for measuring the temperature of wafers that are covered by a blanket layer of metal.

SINGLE-PASS EXPERIMENTS ON PARTIALLY METALLIZED WAFERS

In the single-pass method of temperature measurement, the light is incident on one side of the wafer, transmitted through the wafer and then detected on the other side of the wafer. (Because of the rough wafer surface and fairly low surface reflection (~30%) multiple internal reflections are ignored.) The transmitted signal is normalized by the room temperature signal to remove the effect of scattering from a rough wafer surface on the magnitude of the detected signal. This single-pass geometry has already been used for temperature measurement in RTCVD in the 500-800°C range, using 1.3μm and 1.55μm lasers. [1,2] Below 500°C, however, little absorption is seen with these wavelengths. A shorter wavelength probe beam was needed to give greater sensitivity at lower temperatures due to a higher bandgap absorption. For this experiment, a 1.18μm semiconductor laser was used, along with the 1.3μm laser used previously. The wafer was placed on a resistively heated surface inside a vacuum chamber with nitrogen ambient (500 mtorr). The actual wafer temperature was measured with a thermocouple cemented to the wafer ~10mm from the spot being probed. The silicon wafers used were p-type (10-50Ω), 525μm thick

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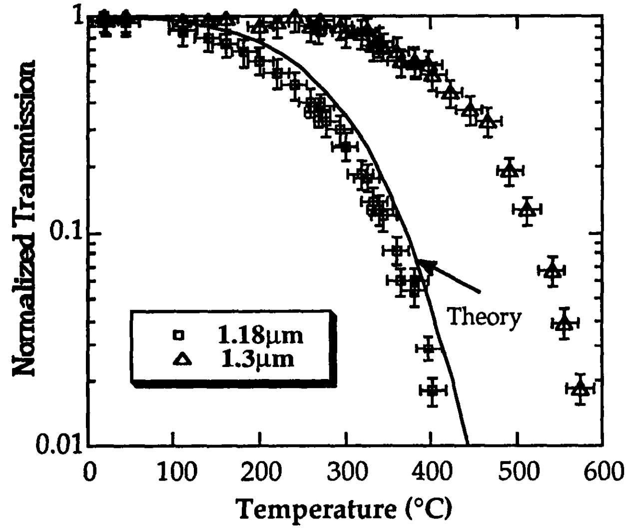

Figure 1: Normalized transmission vs. temperature for 1.18μm and 1.30μm.

and with unpolished backsides. The laser probe beam was modulated electronically, and the transmitted signal was detected with a lock-in amplifier.

In fig. 1, the data of normalized transmission for a bare wafer versus temperature measured by the thermocouple is shown for the wavelengths of 1.18μm and 1.3μm. The error in the temperature measured by the thermocouple is estimated to be ±8°C and the relative error in the normalized transmission to be ±15%. At these wavelengths and low temperatures, free-carrier absorption is negligible and bandgap absorption dominates. Plots of the calculated normalized transmissions versus temperature using the model of ref. [3] are shown. As expected, the normalized transmission at 1.18μm is lower than that at 1.3μm. The sensitivity of this measurement for 1.18μm wavelength at T>300°C is 1%/°C.

In practice, wafers processed in this temperature range may contain varying degrees of metal coverage. Since the metal is opaque to infrared light, varying metal coverage will change the transmitted intensity. However, since the fraction of the light that is blocked is not a function of temperature, one would expect the normalized transmission to be independent of metal coverage. This would be required for a real application, since one would hope to have a transmission versus temperature curve independent of the actual circuit being processed. This was checked for Al metal coverages of 50%, 90%, and 99%. Results are shown in fig. 2, for 1.18μm and 1.3μm after normalizing each wafer's transmission of each wavelength to its room temperature value. Within experimental error, the normalized transmission is indeed independent of metal coverage, so that a normalized transmission versus temperature calibration curve could be used in applications, independent of metal pattern.

DOUBLE-PASS EXPERIMENTS ON BLANKET METALLIZED WAFERS

If the wafer frontside were completely covered with metal, the infrared light would be unable to penetrate the metal and measuring temperature using the single-pass method would not be possible. Such a situation might occur in a self-aligned silicide formation process, where a blanket coating of metal is reacted with silicon exposed through holes in an oxide. We therefore

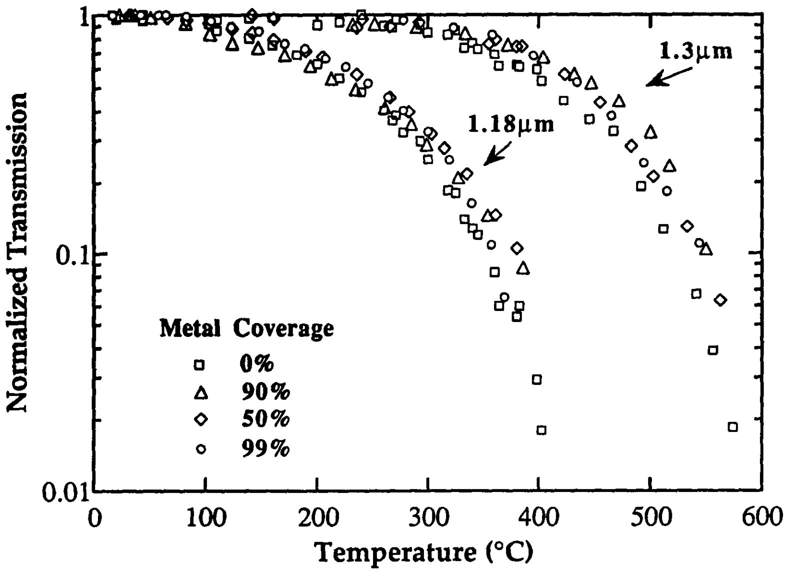

Figure 2: Normalized transmission vs. temperature for various metal coverages.

developed a double-pass technique where the probe beam is incident on the wafer backside (fig. 3) There are two signals which will be sensed by the detector: a signal directly reflected off the backside of the wafer and a double-pass signal, which passes through the wafer, reflects off the metal surface on the front, passes back through the wafer, and is then emitted out the backside. This double-pass signal will be a strong function of temperature because of the absorption in the wafer, and is the one we want to detect. A critical issue is how to separate the desired double-pass signal, which is a strong function of temperature and may be weak, from the direct reflection from the wafer surface, which is a very weak function of temperature.

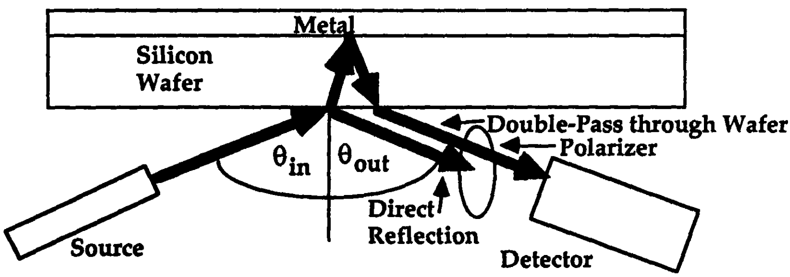

Figure 3: Schematic diagram of the double-pass infrared transmission technique for the temperature measurement of metal-coated silicon wafers. Incident light at Brewster's angle was used to minimize the undesired direct reflection.

This concern was addressed by using an incident beam at Brewster's angle (74° from normal), for which direct reflection is ideally zero for p-polarized light. Ratios of ~10^{-3} for the undesired direct reflection to desired double-pass signals were achieved in practice.

Experiments on double-polished wafers were performed with 1.18μm, 1.3μm, and 1.55μm wavelength laser beams, using both Al and Pt blanket coverages on the front of the wafer (fig. 4). An exponentially decreasing transmission was observed as temperature increased, and the transmission decreased sharply at shorter wavelengths both characteristic of absorption across the bandgap. We compared our double-pass results to the single-pass model developed in [3], using a wafer path length of 2d/cosθ where d is the wafer thickness and θ is the angle from the normal inside the wafer (from Snell's law). The model results (with no adjustable parameters) are also shown in fig. 4. The good agreement confirms that the silicon absorption is indeed being measured and that the direct reflection is not significant. This confirms that the signal detected was the double-pass signal and not direct reflection. The sensitivity for T>200°C for 1.18μm is at least 2%/°C.

For most applications the wafer backside is not polished. This motivated us to extend the double-pass work to wafers with unpolished backsides. We measured the size of the undesired direct reflection versus the desired double-pass signal by using wafers with and without aluminum on the frontsides. These results were compared with those of a wafer with a polished frontside. The rough backsides surface degraded the desired double-pass signal, but the direct reflection was changed little (Table I).

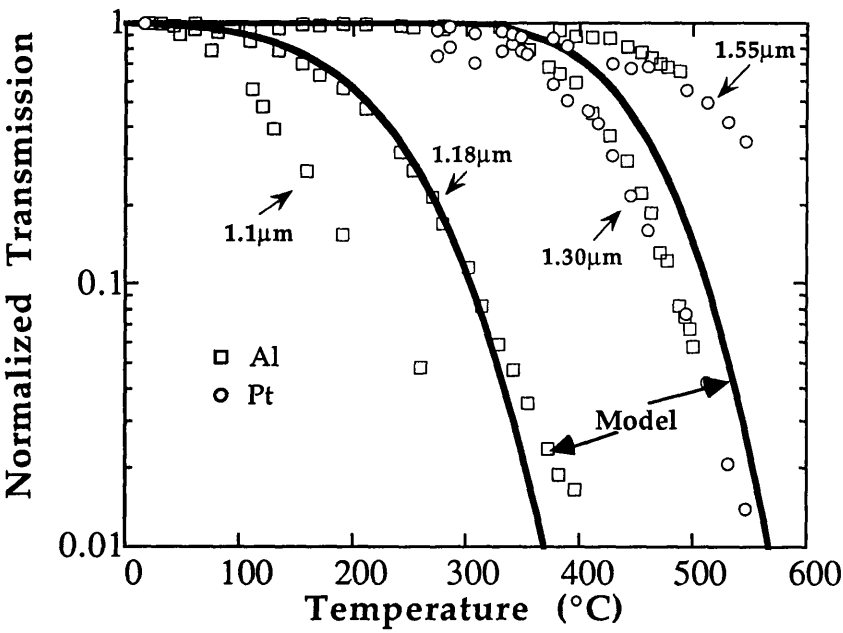

Figure 4: Normalized double-pass transmission data at 1.1, 1.18, 1.3, and 1.55 μm vs. temperature and modeling results.

Table I: Strength of double-pass signal and direct reflection (at room temperature) for metal-coated wafers with polished and unpolished backsides.

Backside	Double Pass	Direct Reflection	Dynamic Range
Polished	200mV	0.18mV	~1000
Unpolished	0.3mV	0.36mV	~1

For rough backsides, the ratio of the undesired reflected signal to the desired double-pass signal at room temperature is near one. Therefore, it is difficult to accurately measure small double-pass signals at high temperatures, as would be required for temperature measurement. Note that the undesired signal is scattered once by surface reflection; whereas the desired double-pass signal is scattered twice since it travels through the interface twice. Independent measurements of the scattering due to roughness showed that this reduction in double-pass signal was indeed due to the rough surface.

At elevated temperatures, the detected signal indeed never decreased to lower than ~50% of its room temperature value because of the scattering of the desired double-pass signal, presumably due to the high direct reflection signal. Therefore, it is not possible to measure temperature as previously implemented due to the interference of the direct reflection signal.

A method to overcome this limitation is now proposed which would allow for the isolation of the double-pass signal from the direct reflection signal. The incident beam could be modulated between two wavelengths, one of which was very low (1.0μm) and would be completely absorbed by the wafer, even at room temperature, and the other whose absorption would vary over the temperature range of interest (1.2μm) (fig. 5). If the intensities of the two wavelengths were equal, then the direct reflections (which is not a strong function of temperature or wavelength) of both wavelengths would be equal. Therefore the desired double-pass signal would be modulated, whereas the DC component contains only the direct reflection. Therefore, a lock-in amplifier synchronized at the modulation frequency would directly detect the double-pass signal with no direct reflection interference. Such experiments are in progress.

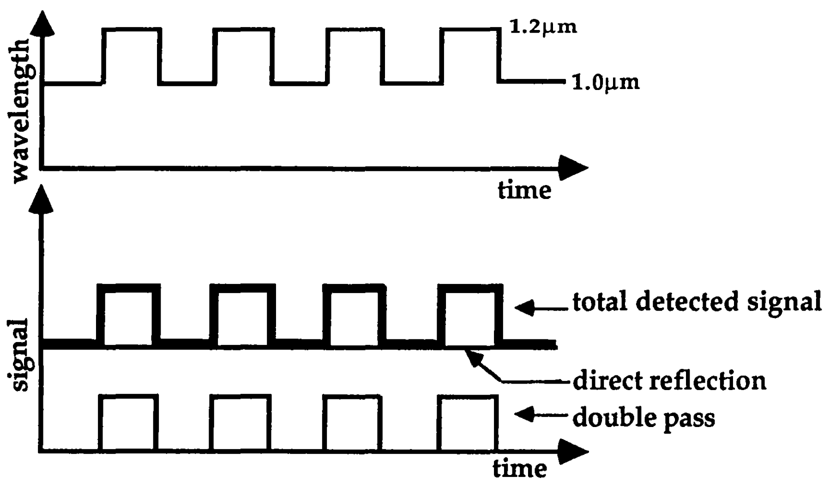

Figure 5: Wavelength and detected signals vs. time for the proposed wavelength modulation technique.

CONCLUSION

Measuring the temperature of silicon by infrared transmission has been extended to partially and blanket metal covered double-polished wafers. Both the single- and double-pass techniques were tested up to 550°C. For the single-pass technique, metal coverages varied from 50% to 99% and the normalized transmission for wafers with rough backsides was independent of metal coverage. The double-pass done on double-polished wafers with blanket metal, but not yet successfully implemented on wafers with rough backsides.

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References

[1] J. C. Sturm, P. V. Schwartz, and P. M. Garone, Appl. Phys. Lett. **56**, 961 (1990).
[2] J. C. Sturm, P. M. Garone, and P. V. Schwartz, J. Appl. Phys., **69**, 542 (1991).
[3] J. C. Sturm and C. M. Reaves, IEEE Trans. Electron Devices, **39**, 81 (1992).