ANOMALOUS EMISSIVITY FROM PERIODIC
MICRO-MACHINED SILICON SURFACES

Peter J. Hesketh

Benjamin Gebhart

Jay N. Zemel

Center for Sensor Technologies and Department of Electrical Engineering
Department of Mechanical Engineering and Applied Mechanics
University of Pennsylvania
Philadelphia, Pennsylvania 19104-6314

Thermal processes involving small micro-machined surface elements have begun to attract an increasing amount of attention. While much of the attention has been directed toward the cooling of integrated circuits, there remains a fundamental question about the nature of the interactions when the characteristic scale of the physical process becomes comparable to the dimensional scale of the local geometry. One of the simpler processes to investigate is the radiant heat transfer from a solid whose surface has been micromachined to form a regular periodic structure, e.g. a deep grating or a two dimensional array of pits or hillocks. Such surfaces will be referred to as micro-configured surfaces. Microconfigured surfaces have potential applications as adsorbers of gases, absorbers of radiation, and microheat exchangers. The results reported here are, to the best of our knowledge, not only the first experimental study of the thermal emissivity of deep gratings, but is also a subject for which essentially no direct theoretical study has been performed. A deep grating is defined as one where the ratio of the depth of the grating, h , to repeat distance or characteristic geometric scale, S , is equal to or greater than 0.5. The emissivity measurements were conducted in the range $0.14 \leq \lambda/S \leq 0.68$ where λ is the measured electromagnetic radiation wavelength. The resulting data demonstrated that surface geometry plays a highly significant role in the emissivity.

The experiments employed (110) oriented silicon wafers on which a $22\mu\text{m}$ "square wave" grating is etched to various depths using standard photolithography and a 40%wt. solution of KOH at 52°C . The width of the silicon ridge is $11\mu\text{m}$ as shown schematically in Figure 1a). A scanning electron micrograph of a $22\mu\text{m}$ deep grating is shown in Figure 1b). The peak amplitude to half width ratio, A , for this structure is $A=2$. Another grating with $A=4$ has also been investigated. After etching, the microconfigured wafers are then spin-coated with a phosphorus based dopant which is heated to 1250°C for 10 hours. The phosphorus surface concentration is in the $0.6\text{--}1.1 \times 10^{20}/\text{cm}^2$ regime which yields an effective skin depth for $\lambda > 5\mu\text{m}$ of $2\mu\text{m}$ or less. The back surface of the silicon wafer was also heavily doped to act as the heater element. A blackbody was constructed and its temperature was stable to better than $10\text{m}^\circ\text{C}$ during the course of the measurements. The temperature of the blackbody was used as a reference against which the temperature of the silicon sample was stabilized with a feedback control loop. Temperature fluctuations were typically less than 0.1°C during the course of measurement.

The initial studies were on silicon chips containing the microconfigured surface that had been sliced from the wafer. These chips were mounted in a specially designed low thermal loss holder. Calculators indicated that the thermal losses other than radiation are about 40% of the total energy input. In the temperature range used, $300^\circ\text{C} < T < 400^\circ\text{C}$, significant difference in the energy input required to reach operating temperatures were observed for smooth and microconfigured surfaced samples. The emissivity measurement consisted of the black body source, the sample, a reflection system that permits viewing of the silicon surface, both smooth and microconfigured, down to azimuthal angles of 75°C , as shown in Figure 2. The polar angle drive was controlled by a computer driven stepping motor thereby allowing the polar angle dependence of the emissivity to be measured with good precision. Measurements were carried out for azimuthal directions parallel ($\phi=0^\circ$) and perpendicular ($\phi=90^\circ$) to the grooves. The polarization measurements employed a Perkin-Elmer infrared polarizer at the slits of a Perkin-Elmer 112 NaCl prism spectrometer. A Judson HgCdTe infrared detector was used to measure the intensity of the radiation. The data was logged on a computer controlled system and that also controlled the stepping motor.

The basic measurements are shown in Figures 3 and 4. In Figure 3a), the wavelength dependence of the emissivity for both s and p polarization is shown for $\phi=0^\circ$ and $\theta=0^\circ$. Note the oscillatory and complementary character of the emissivity. A plot of the peak λ positions versus an integer yields a linear rather than a parabolic relation as seen in Figure 3b). The polar angular dependence of the emissivity is quite extraordinary. In Figures 4a) ($\phi=90^\circ$, a polarized radiation), 4b) ($\phi=0^\circ$, p polarized radiation), and 4c) ($\phi=0^\circ$, s polarized radiation), the polar angle position of the maxima in the emissivity decrease with increasing wavelength as shown in Figure 4e). However, in Figure 4d), ($\phi=90^\circ$, p polarized radiation) the emissivity does not show any pronounced peaks. Essentially the same behavior was observed on a sample with the same S value but $A=4$. The only plausible explanation available at present for both the mode and angular dependence of these measurements is that the grating couples a surface polariton to a radiative mode of the sample.

Two of the authors (P.H. and J.N.Z.) wish to acknowledge the partial support of the EEMS Program of NSF, D. Silversmith, Program Manager, under Grant ECS-84-12241. The authors wish to thank Professor H. Baltes for useful discussions and one of us (J.N.Z.) wishes to thank Professor A. Maradudin for a helpful conversation.