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Rapid Thermal and Integrated Processing V

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R.P.S. Thakur
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PREFACE

This symposium volume, "Rapid Thermal and Integrated Processing V," from the 1996 MRS Spring Meeting, embraces a diversity of research, development and manufacturing activities that require rapid thermal and integrated processing techniques which are recognized by their acronyms of RTA (rapid thermal annealing), RTP (rapid thermal processing), RTCVD (rapid thermal chemical vapor deposition), (RTO rapid thermal oxidation), and various extensions thereupon. Although most of the articles deal with processing issues directed towards silicon-based electronics, several novel applications, such as the papers in Part IV, are especially welcomed contributions. This fifth anniversary volume reports notable advances in the use of rapid thermal techniques in processing science and technology, in equipment capability for manufacturing and research needs, and for process control in industrial fabrication facilities. This year's symposium is organized around progress obtained through evaluation methodology, equipment and process modeling, temperature control, defects and diffusion associated with annealing, metallizations such as silicidation, novel processing of sol-gel and magnetic films, dielectric growth and deposition, and silicon or silicon-germanium film deposition.

The organizers and participants appreciate generous symposium support from the processing equipment vendor companies, A.G. Associates, AST Elektronik, CVC Products, and Mattson Technology. The editors also acknowledge the Materials Research Society and Lucent Technologies for assistance in preparation of this volume, the assistance of session chairpersons Chuck Schietinger and Tony Speranza, and the numerous anonymous referees who generously gave up their time to review the proceedings papers.

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Part I

Evaluation, Modeling and Temperature Control I

THE ROLE OF THERMAL RADIATIVE PROPERTIES OF SEMICONDUCTOR WAFERS IN RAPID THERMAL PROCESSING

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ABSTRACT

Rapid thermal processing (RTP) has become a key technology in the fabrication of advanced semiconductor devices. As RTP becomes the accepted technique for an increasingly wide range of processes in device fabrication, the understanding of the basic physics of radiation heat transfer in RTP systems is also being extended rapidly. This paper illustrates the use of optical models for prediction of the thermal radiative properties of semiconductor wafers. Such calculations can be used to address many of the key issues of interest in RTP, including questions concerning temperature measurement and process repeatability.

INTRODUCTION

The transfer of energy by thermal radiation lies at the heart of all commercial RTP technology. For this reason, a thorough understanding of the thermal radiative properties of semiconductor wafers is essential for the development of RTP systems for semiconductor manufacturing [1,2]. Fig. 1 illustrates the significance of these properties in RTP. The most fundamental property is the spectral emissivity, $\varepsilon(\lambda,\theta,\phi,T)$, which is the ratio of the radiation emitted by a wafer with temperature T, at a given wavelength, λ, angle of incidence, θ, and plane of polarization, ϕ, to that emitted from a blackbody under the same conditions. In general, it is also a function of the azimuthal angle if the surface does not have azimuthal symmetry. The azimuthal dependence will be ignored in this paper, although it can play a significant role in the behaviour of radiation emitted from patterned surfaces [3]. The spectral emissivity of a surface must be known when the wafer's temperature is measured using a pyrometer. According to Kirchhoff's law,

$$a(\lambda,\theta,\phi,T) = \varepsilon(\lambda,\theta,\phi,T), \quad (1)$$

where $a(\lambda,\theta,\phi,T)$ is the spectral absorptivity, which can be calculated from the optical properties of the materials which make up the wafer [1]. Two other properties of great interest in RTP are the total absorptivity and the total emissivity of the wafer. The total absorptivity can be viewed as a measure of the efficiency of coupling lamp radiation to the wafer, whereas the total emissivity affects the total heat loss by radiation from the wafer. These quantities are integrated radiative properties, which describe behaviour averaged over ranges of wavelengths and angles of incidence. The relevant spectral and angular ranges depend on the geometry of the RTP system and the nature of the heat source. For example, in free space, the total radiation heat loss from a surface is governed by the total

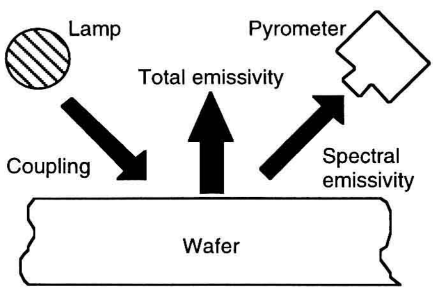

Fig. 1 The thermal radiative properties of semiconductor wafers play a key part in RTP.

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hemispherical emissivity, $\varepsilon_{tot}(T)$, which is related to the spectral emissivity by the equation,

$$\varepsilon_{tot}(T) = \frac{2\int_{\theta=0}^{\pi/2}\int_{\lambda=0}^{\infty}\varepsilon_u(\lambda,\theta,T)W_{bb}(\lambda,T)\sin\theta\cos\theta d\theta d\lambda}{\sigma T^4}, \qquad (2)$$

where the term in the denominator is the total power radiated by a blackbody, as given by the Stefan-Boltzmann law, and σ is the Stefan-Boltzmann constant. $W_{bb}(\lambda,T)$ is the spectral radiant exitance, which is given by the Planck function, and describes the power per unit area and wavelength radiated into the forward hemisphere from a blackbody [1]. In Eqn. (2) $\varepsilon_u(\lambda,\theta,T)$ is the spectral emissivity for unpolarized radiation, which is equal to the average of the spectral emissivity for radiation polarized parallel to the plane of incidence (the p-polarization) and that polarized perpendicular to the plane of incidence (the s-polarization). For the purposes of modelling radiation heat transfer in real RTP systems, other spectral and angular ranges may be more appropriate than those in Eqn. (2). For example, in systems in which the wafer is surrounded by a quartz isolation tube, it may be convenient to examine the integrated properties over the wavelength range where the quartz is transparent, $\lambda < 4\mu m$, or opaque $\lambda > 4$ μm [4]. Similar considerations apply in calculation of the total absorptivity, which depends on the spectral and angular qualities of the radiation heat sources, as well as the geometry of the chamber.

OPTICAL PROPERTIES OF SEMICONDUCTOR WAFERS

Thermal radiative properties are essentially optical properties, because they depend only on the way in which electromagnetic waves interact with a given object. Given the optical properties of the materials present in a wafer and a complete description of the geometry, one could in principle calculate the spectral emissivity, and all the other thermal radiative properties of interest in RTP. The main difficulty in making reliable predictions of radiative properties lies in the need for accurate values for the absorption coefficients and refractive indices of many materials covering large ranges of wavelengths and temperatures. The optical properties of interest depend on the phenomenon being modelled. For example, the thermal radiative properties of lightly doped wafers at temperatures < ~700°C are strongly influenced by the absorption coefficient of the silicon substrate, but at temperatures > ~750°C a typical wafer is opaque and the nature of the wafer's surfaces dominates the behaviour [1]. Ideally, one would have values for the optical constants for wavelengths between 0.4 and 20 μm, at temperatures up to 1200°C. For many materials, especially semiconductors, impurity content and crystalline microstructure affect the optical properties, which greatly adds to the data required to cover every conceivable semiconductor wafer. Nevertheless, it is currently possible to make accurate predictions of the behaviour of many wafers, using published data and models, and this paper will include some examples of this rapidly expanding knowledge base. An extensive list of references for optical properties of semiconductors and other wafer-related materials at elevated temperatures can be found in Ref. 1.

Silicon is by far the most important semiconductor, and its optical properties have been studied extensively, both at room temperature and above [1,5-17]. Its absorption spectrum exhibits features associated with fundamental absorption, free-carrier effects and lattice vibrations. At short wavelengths, the photon energy is large enough to produce electron-hole pairs, and the absorption coefficient is very large. As the wavelength increases and the photon energy becomes smaller than the silicon band-gap, there is a rapid drop in absorption, which is called the absorption edge. At longer wavelengths absorption occurs by interaction with free-carriers and lattice vibrations. Fig. 2 shows some recent measurements of the absorption spectrum of lightly doped silicon at elevated temperatures, and includes theoretical predictions based on a model which accounts for the