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Rapid Thermal and Integrated Processing V

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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.

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CONTENTS

Preface	xi
Materials Research Society Symposium Proceedings	xii

PART I: EVALUATION, MODELING AND TEMPERATURE CONTROL I

*The Role of Thermal Radiative Properties of Semiconductor Wafers in Rapid Thermal Processing	3
<i>P.J. Timans</i>	
Evaluation of Applied Materials' Rapid Thermal Processor Using SEMATECH Methodologies for 0.25 μm Technology Thermal Applications-Part I	15
<i>Terrance J. Riley, Arun K. Nanda, Gary Miner, Michael F. Pas, Sylvia Hossain-Pas, and Lino A. Velo</i>	
Evaluation of Applied Materials' Rapid Thermal Processor using Sematech Methodologies for 0.25 μm Technology Thermal Applications-Part II.	23
<i>Arun K. Nanda, Terrence J. Riley, Gary Miner, Michael F. Pas, and Sylvia Hossain-Pas</i>	
Response Surface Technique for <i>Ex Situ</i> Process Uniformity Optimization in a Multi-Zone RTP System	31
<i>Karson L. Knutson and Thomas L. Cooper</i>	
Monte Carlo Thermal Model of an Integrating Light Pipe for Rapid Thermal Processing	37
<i>J.C. Thomas and D.P. DeWitt</i>	
The Effect of Multilayer Patterns on Thermal Stress During Rapid Thermal Processing	43
<i>Jeffrey P. Hebb and Klavs F. Jensen</i>	
Numerical Modeling of Radiative Properties of Patterned Wafers With Sub-Micron Features	51
<i>Jeffrey B. Hoppert, Ioannis N. Miaoulis, and Peter Y. Wong</i>	
Nonlinear Model Reduction Strategies for Rapid Thermal Processing Systems	57
<i>Suman Banerjee, J. Vernon Cole, Klavs F. Jensen, and A. Emami-Naeini</i>	

*Invited Paper

Application of Holographic Interferometry to Flow Pattern Visualization in an RTCVD Reactor	65
<i>Yu.P. Rainova, J. Pezoldt, K.I. Antonenko, and G. Eichhorn</i>	

Strategies for the Reduction of Pattern Effects	71
<i>A. Kersch, T. Schafbauer, and L. Deutschmann</i>	

PART II: RAPID THERMAL ANNEALING-DIFFUSION AND DEFECTS

*How Rapid Isothermal Processing Can Be a Dominant Semiconductor Processing Technology in the 21st Century	81
<i>R. Singh, R. Sharangpani, K.C. Cherukuri, Y. Chen, D.M. Dawson, K.F. Poole, A. Rohatgi, S. Narayanan, and R.P.S. Thakur</i>	

Accurate Estimation of Radiative and Convective Losses in a Multizone RTP Reactor	95
<i>R.V. Nagabushnam, R.K. Singh, S. Sharan, and G. Sandhu</i>	

Effects of a Post-Emitter RTP on Bipolar NPN Beta Degradation Lifetime for 1.0 Micron & 0.8 Micron BICMOS Processes	103
<i>W.E. Leitz, G. Modi, N. Parekh, E. Sabin, and R.V. Taylor</i>	

Self-Interstitial Supersaturation During Ostwald Ripening of End-of-Range Defects in Ion-Implanted Silicon	109
<i>M. Seibt</i>	

RTA Processing of W-Polycide Dual-Gate Sub-Micron Structures for Low-Voltage CMOS Technology	115
<i>J. Bevk, M. Furttsch, G.E. Georgiou, S.J. Hillenius, D. Schielein, T. Schiml, P.J. Silverman, and H.S. Luftman</i>	

Measurement of Lateral Dopant Diffusion in Rapid Thermal Annealed W-Polycide Gate Structures	121
<i>T. Schiml, J. Bevk, M. Furttsch, G.E. Georgiou, R. Cirelli, W.M. Mansfield, P.J. Silverman, and H.S. Luftman</i>	

Rapid Thermal Dopants Diffusion and Surface Passivation for Silicon Solar Cells Applications	127
<i>Abdelilah Slaoui, Aziz Lachiq, Laurent Ventura, and Jean Claude Muller</i>	

General Kinetic Rules for Rapid Thermal Processing	133
<i>R. Ditchfield and E.G. Seebauer</i>	

*Invited Paper

PART III: METALLIZATION

Effect of Nitrogen Diffusion in Ti and Ti/TiN Films for Future DRAM Bit Line Interconnects and Plugs	141
<i>John M. Drynan and Kuniaki Koyama</i>	
Post Metallization Damage Recovery Using Rapid Thermal Processing (RTP)	153
<i>R.P.S. Thakur, F. González, and S. DeBoer</i>	
Study of Cobalt Salicide Fabrication on Sub-Quarter Micron Polysilicon Lines	163
<i>Wei-Ming Chen, Scott Pozder, Young Limb, A.R. Sitaram, and Bob Fiordalice</i>	
Improvement in Platinum Silicidation for 0.8 μm BICMOS Process	169
<i>Suketu Parikh, Gaurang Modi, and Samuel Nagalingam</i>	
Modeling of Device Characteristics as Function of Ti Salicide Rapid Thermal Processing Parameters for Deep-Sub-Micron CMOS Technologies	175
<i>J.A. Kittl, D.A. Prinslow, G. Misium, and M.F. Pas</i>	
Correlation Between the Standard Deviation of Sheet Resistance and the Temperature of Rapid Thermal Annealing	181
<i>X.W. Lin and D. Pramanik</i>	
<i>In Situ</i> Rapid Thermal Hydrogenation Pretreatment of Ti for Salicide RTA	187
<i>K. Ando, T. Ishigami, Y. Matsubara, T. Horiuchi, and S. Nishimoto</i>	

PART IV: NOVEL RAPID THERMAL PROCESSES

*UV Photoannealing and RTP of Thin Sol-Gel Films	193
<i>R.E. Van de Leest and F. Roozeboom</i>	
Rapid Thermal Magnetic Annealing: A Novel Technique in Thin-Film Recording Head Production?	203
<i>Fred Roozeboom, Jaap J.M. Ruigrok, Wilco Klaassens, Herbert Kegel, Manfred Falter, and Heinrich Walk</i>	

*Invited Paper

PART V: DIELECTRICS

Studies of the Effect of Various Gas Species on Si-SiO₂ Interface Charges and Surface Roughness for Rapid Thermal Deposited Gate Oxides	213
<i>A.M. Bayoumi and J.R. Hauser</i>	
Influence of HCL on Rapid Thermal Oxides	219
<i>G.A. Hames, S.E. Beck, A.G. Gilcinski, W.K. Henson, and J.J. Wortman</i>	
Thin Nitride Films: Pushing the Limits Using Rapid Thermal Processing	225
<i>S.J. DeBoer and R.P.S. Thakur</i>	
Bonded-H in Gate Dielectrics Deposited by Plasma Assisted Chemical Vapor Deposition and Subjected to Rapid Thermal Annealing	233
<i>G. Lucovsky, H. Nimi, and K. Koh</i>	
Nitrided Gate Dielectrics and Charge-to-Breakdown Test	239
<i>S. Dimitrijevic, P. Tanner, H.B. Harrison, and D. Sweatman</i>	
Characterisation of Dielectric Damage in MOS Capacitors by a New Current Transient Measurement Technique	245
<i>P.G. Tanner, Sima Dimitrijevic, Y-T. Yeow, and H.B. Harrison</i>	
Study of Nitrogen Incorporation in Gate Oxides Using the Resistance to Oxidation Method	251
<i>L. Sagnes, D. Laviale, M. Regache, F. Glowacki, L. Deutschmann, B. Blanchard, and F. Martin</i>	
Rapid Thermal Oxidation of Silicon in Mixtures of Oxygen and Nitrous Oxide	257
<i>John M. Grant and Zia Karim</i>	
Development of a Cluster Tool and Analysis of Deposition of Silicon Oxide by TEOS/O₂ PECVD	263
<i>N.I. Morimoto and J.W. Swart</i>	
Low Temperature Oxidation Processing With High Purity Ozone	269
<i>A. Kurokawa, S. Ichimura, H.J. Kang, and D.W. Moon</i>	

GOI Impact of Cu, Ni and Al Atoms on the Wafer Surface Prior to RTP and Furnace Oxidations	275
<i>W.R. Aderhold, N. Shah, S. Bogen, A. Bauer, and E.P. Burte</i>	

PART VI: EVALUATION, MODELING AND TEMPERATURE CONTROL II

*Wafer Temperature Measurement: Status Utilizing Optical Fibers	283
<i>Chuck Schietinger and Earl Jensen</i>	
Temperature Monitoring by Ripple Pyrometry in Rapid Thermal Processing	291
<i>Binh Nguyenphu, Minseok Oh, and Anthony T. Fiory</i>	
Effects of Reflective Surfaces on Silicon Emissivity and Temperature Measurements	297
<i>H. Xu and J.C. Sturm</i>	
*Temperature Measurement at RTP Facilities-An Overview	303
<i>J. Wagner and F.G. Boebel</i>	
*Commercial RTP-A SEMATECH Perspective	309
<i>Tony Speranza, Terry Riley, Arun Nanda, Burt Fowler, Kenneth Torres, Franz Geyling, and Don Lindholm</i>	
Emissivity Independent Process Control in a Short Wavelength Arc Lamp RTP Chamber	321
<i>Marcel E. Lefrançois, David M. Camm, and Brendon J. Hickson</i>	
Pattern Related Non-Uniformities During Rapid Thermal Processing	327
<i>R. Bremensdorfer, S. Marcus, and Z. Nenyel</i>	
Estimation of Emissivity of a Wafer in an RTP Chamber by a Dynamic Observer	335
<i>Sergey Belikov, David Hur, Bernard Friedland, and N.M. Ravindra</i>	

PART VII: RTCVD OF Si AND SiGe

Sub-Half Micron Elevated Source/Drain NMOSFETS by Low Temperature Selective Epitaxial Deposition	343
<i>J. Sun, R.F. Bartholomew, K. Bellur, P.A. O'Neil, A. Srivastava, K.E. Violette, M.C. Öztürk, C.M. Osburn, and N.A. Masnari</i>	

*Invited Paper

Selective Deposition of Silicon and Silicon-Germanium Alloys by Rapid Thermal Chemical Vapor Deposition	349
<i>John M. Grant, Ming Ang, and Lynn R. Allen</i>	
Low Temperature Selective Si Epitaxy Using Si₂H₆ and Cl₂: Investigations into Selectivity Robustness and Epitaxial Film Quality	355
<i>Patricia A. O'Neil, Katherine E. Violette, Mehmet C. Öztürk, Dale Batchelor, and Dennis M. Maher</i>	
Integrated Two-Stage Processing of Microcrystalline Silicon Thin Films on SiO₂ and Glass	361
<i>D. Wolfe, F. Wang, and G. Lucovsky</i>	
Silicon Thin Film Homoepitaxy by Rapid Thermal Atmospheric-Pressure Chemical Vapor Deposition (RT-APCVD)	367
<i>Rémi Monna, Detlef Angermeier, Abdellah Slaoui, and Jean Claude Muller</i>	
Electron Cyclotron Resonance in Strained Si and Si_{0.94}Ge_{0.06} Channels on Relaxed Si_{0.62}Ge_{0.38} Buffers Grown by Rapid Thermal Chemical Vapor Deposition	373
<i>C.W. Liu and V. Venkataraman</i>	
Memory Effect in RTCVD Epitaxy of Si and SiGe	379
<i>G. Ritter, B. Tillack, and D. Wolansky</i>	
Author Index	385
Subject Index	387

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, $\epsilon(\lambda, \theta, \phi, T)$, 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,

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

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

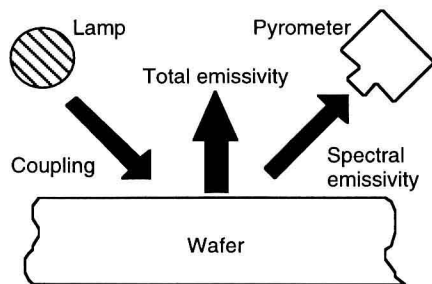


Fig. 1 The thermal radiative properties of semiconductor wafers play a key part in RTP.

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

$$\epsilon_{\text{tot}}(T) = \frac{2 \int_{\theta=0}^{\pi/2} \int_{\lambda=0}^{\infty} \epsilon_u(\lambda, \theta, T) W_{bb}(\lambda, T) \sin \theta \cos \theta d\theta d\lambda}{\sigma T^4}, \quad (2)$$

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) $\epsilon_u(\lambda, \theta, T)$ 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, $\lambda < 4\mu\text{m}$, or opaque $\lambda > 4\mu\text{m}$ [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 $< \sim 700^\circ\text{C}$ are strongly influenced by the absorption coefficient of the silicon substrate, but at temperatures $> \sim 750^\circ\text{C}$ 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 $20\mu\text{m}$, 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