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Device scaling effect on the spectral-directional absorptance of wafer's front side

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Abstract

Nonuniform absorption of thermal radiation in the rapid thermal processing of wafers is a critical problem facing the semiconductor industry. This paper presents a parametric study of the radiative properties of patterned wafers with the smallest feature dimension down to 10 nm, considering the effects of temperature, wavelength, and angle of incidence. Various gate and trench sizes and their dimensions relative to the period are used in examining the effect of device scaling on the spectral-directional absorptance via numerical solutions of the Maxwell equations. In the cases with trench size variation, the resonance cavity effect may increase the absorptance as the trench width increases. In the cases with trench size increases at several different filling ratios, the absorptance does not change much at small filling ratio. Wood's anomaly appears in the directional-hemispherical absorptance with gates on top of silicon substrate.

Keywords: Rapid thermal processing; Finite-difference time-domain; Rigorous coupled-wave analysis; Periodic nano-structures

1. Introduction

According to the International Technology Roadmap for Semiconductors [1], the gate length and junction depth of the 65-nm devices used in high-performance complementary metal oxide semiconductor (CMOS) technology will be 25 and 13.8 nm, respectively. Rapid thermal processing (RTP) currently provides the high-temperature annealing needed to create ultra-shallow junctions. However, the ion implantation annealing time, which ranges from 1 to 10 s above 1000 °C in conventional RTP, is too long to confine ion diffusion and achieve the implanted doping distribution within the junction. This difficulty can be overcome by using high-intensity flash-lamps or laser annealing with heating pulses lasting only a few milliseconds [2]. The typical energy sources are Ar or Xe arc lamps, which mainly emit ultraviolet and visible radiation. In flash-lamp heating, optical energy is absorbed at the wafer front side because of the small penetration depth that results from the large absorption coefficient of Si within the lamp spectrum.

Because the energy is absorbed within milliseconds, thermal diffusion cannot distribute heat uniformly across the wafer surface. Therefore, temperature uniformity across the wafer continues to be a critical issue even with the new annealing processes. Temperature nonuniformity may cause uneven activation of the implants, as well as excessive thermal stresses that can introduce crystallographic defects [3]. One major reason for the temperature nonuniformity arises from the difference in the absorptance of various device patterns in different regions of the wafer surface. Several studies have examined the radiative properties of different patterned structures on wafers and obtained reasonable agreement with experimental results. A quick review is given by Chen et al. [4].

Radiative properties of nano-structures may be very different from those of microstructures made of similar

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Nomenclature

d	depth, m	$\hat{\varepsilon}$	electrical permittivity, $C^2/N\,m^2$
$\mathbf{E}$	electric field vector, V/m	$\hat{\mu}$	magnetic permeability, $N\,s^2/C^2$
$\mathbf{H}$	magnetic field vector, C/m s	$\hat{\sigma}$	electrical conductivity, $C^2/N\,m^2\,s = (\Omega\,m)^{-1}$
i	square root of (-1); node index	$\hat{\sigma}_M$	magnetic conductivity, $N\,s/C^2$
j	diffraction order; node index	ε_e	equivalent electrical permittivity, $C^2/N\,m^2$
$\mathbf{K}$	grating vector, m^{-1}	σ_e	equivalent electrical conductivity, $C^2/N\,m^2\,s = (\Omega\,m)^{-1}$
$\mathbf{k}$	wavevector, $2\pi/\lambda$, m^{-1}	ε	dielectric function
l	length, m	θ	polar angle, rad
n	refractive index; superscript for time step	κ	extinction coefficient, m^{-1}
r_{pq}	Fresnel reflection coefficient from medium p to q	λ	wavelength in vacuum, m
t	transmission coefficient	ϕ	filling ratio
t_{pq}	Fresnel transmission coefficient from medium p to q	ψ	amplitude of the magnetic field, C/m s

Greek symbols

α	absorptance
γ	phase difference, rad

materials [5]. It is essential to know the spectral-directional absorptance of the patterned wafers across a broad range of wavelengths, including the ultraviolet region, so the amount of energy absorbed from the flash-lamp can be determined accurately. The feature size of the new generation of semiconductor devices is already below 65 nm, which is smaller than the wavelength (200–1000 nm) of the flash-lamp annealing heat sources. Little is known about the influence of nanoscale patterns on the radiation absorption and reflection during the millisecond annealing process. The objective of the present research is to continue the prior work by Chen et al. [4] to model the radiative properties of periodically patterned wafers that include features expected in advanced CMOS device technologies. The effects of wafer temperature, wavelength, polarization, and angle of incidence on the spectral directional-hemispherical directional absorptance are investigated for selected two-dimensional (2D) patterned structures with multilayer gratings. In the present study, the rigorous couple wave analysis (RCWA) [6–9] and finite-difference time-domain (FDTD) methods are employed to numerically solve the Maxwell equations and obtain the radiative properties of various wafer front side geometries. For periodic structures, RCWA can produce accurate solutions much faster than FDTD. The FDTD method incorporates a Debye time-domain optical property model for treating the Si optical constants at the wavelengths where the extinction coefficient (κ) is greater than the refractive index (n) [10].

Previous studies have used the method of homogenization or effective medium theory (EMT), in which the grating region is treated as a homogeneous layer with an effective dielectric function. This way, the 2D patterned structures are simplified to planar multilayer structures, which allows the use of very fast calculations based on the matrix equations of thin film optics [11,12]. The EMT is often helpful for understanding the behavior of subwavelength gratings with small period-to-wavelength ratios. By using RCWA in the small-depth limit, it has been shown that the effective properties of subwavelength gratings strongly depend on the grating depth [13]. Moreover, the effective properties have been shown to depend not only on the grating structure but also on the optical indices of the surrounding media. A simple expression for the effective indices of 1D and 2D gratings with arbitrary depths was proposed. Comparison with rigorous computations showed that for transverse electric polarization of 1D gratings the depth dependence of the effective index prediction is accurate [13].

In this study, the structures considered include Si gratings and SiO_2 trenches embedded in the Si substrate. The wavelength range of the radiation from the heat source covers from 200 to 1000 nm. The incident radiation is at normal or arbitrary angles of incidence with the plane of incidence perpendicular to the gratings or trench lines. Earlier investigations explored the behavior for relatively simple patterns with features on the order of micrometers and at wavelengths longer than 400 nm, i.e., ultraviolet wavelengths were not considered [14–17]. This study expanded the prior work by the authors. Furthermore, extensive feature size variations, in conjunction with the wavelength variations, were considered for three different nano-structures on the wafer front side. The effects of the resonant cavity, diffraction, wave interferences on the spectral-directional absorptance were discussed.

2. Theoretical analysis

Two rigorous methods were used in this work: FDTD and RCWA. A much simpler and physically intuitive EMT was also used to help explain the absorptance pre-