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Color variations of silicon-on-insulator wafers with silicon device layer thickness

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Abstract: The perceived colors of silicon-on-insulator (SOI) wafers with etched Si surface layers of thickness 90 nm to 30 nm vary from turquoise to purple to golden. Measured reflectance curves spanning ultraviolet, visible, and near infrared wavelengths have an amplitude modulated oscillatory pattern. Multilayer reflectance calculations indicate the oscillatory pattern results from the 2 µm thick buried SiO_2 layer which functions as a nearly lossless reflective Fabry-Perot etalon in the near infrared where SiO_2 and Si are transparent. The amplitude modulation of the oscillatory pattern in the visible region where Si is absorbing results from thin-film effects in the Si surface layer. The changing modulation with Si thickness and wavelength results in the observed color variations. It is therefore possible to estimate the Si thickness based on the etched SOI wafer color observed visually. This ability is useful when initially optimizing the etching process to produce a specific thin Si layer, for example when fabricating photodiodes or other photonic devices on SOI wafers. Accurate measurements of the Si thickness and the buried SiO_2 thickness can be performed by analyzing the modulated oscillatory reflectance curve using multilayer reflectance calculations.

1. Introduction

Color variations of SOI wafers with thin Si surface layers were observed by Clapis, Ledger, and Daniell [1]. Based on reflectance calculations, they recognized that the color variations perceived by eye resulted from variations in the surface Si layer thickness, and that the eye can discern color variations resulting from Si thickness changes as small as 1 nm.

The colors perceived by the human visual system (HVS) are subjective and depend on lighting conditions, angle of incidence, field of view, and other factors [2]. In this paper, the color variations of SOI wafers with variable Si surface layer thicknesses are quantified by measuring the wafer reflectance and by comparisons with multilayer reflectance calculations.

Using the measured and calculated reflectance curves, the International Commission on Illumination (CIE) tristimulus values are calculated using standard CIE illuminant and observer conditions. The sRGB values are calculated and are used to display colors in this paper. It should be noted that the displayed sRGB colors can vary among different color display programs and applications, computer monitors, and printers.

The CIE color variation parameters u* and v* are device-independent and are calculated for SOI wafers having Si surface layer thicknesses from 20 nm to 110 nm and with 2 µm buried SiO_2 layers. The result is that the Si surface layer thickness can be measured to ± 2 nm accuracy, and the buried SiO_2 layer thickness can be measured to ± 20 nm accuracy.

2. SOI wafer colors

The etched SOI wafers were utilized for the fabrication of UV photodiodes having a thin Si active layer, 100% internal quantum efficiency, and functioning as direct band gap devices with low visible light sensitivity (solar blind) [3]. The starting SOI wafers, prior to etching, were designed

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to have 90 nm thick Si surface layer and 2 µm buried SiO_2 layer on a 525 µm thick Si handle wafer as shown schematically in Fig. 1. The color of an unetched wafer perceived by eye was turquoise. A wafer that was immersed in a buffered oxide etch (BOE) solution for 20 min. had purple color, and a wafer etched for 40 min. had golden color. The colors of the three wafers and the sRGB values measured by a portable colorimeter are shown in Fig. 2.

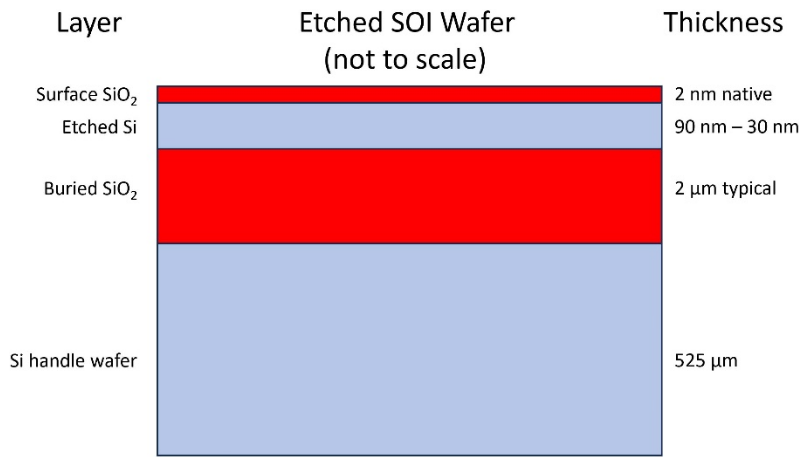

Fig. 1. Schematic of the SOI wafer with a thin etched Si layer.

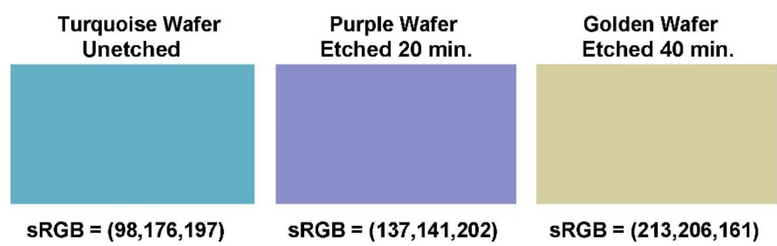

Fig. 2. Wafer colors and measured sRGB values.

The specular reflectances of the three wafers were measured using a xenon lamp and a spectrometer in the wavelength range 360 nm to 900 nm. The air-cooled xenon lamp, powered by a constant current and constant voltage regulated power supply, provided a stable continuum spectrum free of spectral lines and absorption features except for weak air absorption at the longer NIR wavelengths. The measured wafer reflectance was divided by the measured reflectance of a reference mirror, both at 10^o angle of incidence. The final reflectance curve is the product of this ratio and the known reflectance of the reference mirror. The reference mirror was aluminum with a dielectric coating that resulted in $> 98\%$ reflectance over the ultraviolet-visible-near infrared (UV-VIS-NIR) measurement range. The reflectance of the reference mirror was verified by reflectance measurements using six laser diodes spanning the 405 nm to 786 nm wavelength range. Laser diode measurements were also used to characterize the linearity, spectral resolution (1.4 nm), scattered light level (1.5%), and second diffraction order contributions (negligible) of the spectrometer measurements and to establish an accurate wavelength scale (± 0.3 nm).

The measured reflectance curves are shown in Fig. 3(a) along with the CIE eye sensitivity curve with visible spectral colors. The reflectance curves have a modulated oscillatory appearance. The reflectance curves multiplied by the eye sensitivity are shown in Fig. 3(b). The reflectance of the turquoise (unetched) wafer is highest in the green-blue region, the purple wafer has two peaks with nearly equal values, and the golden wafer is highest in the yellow-orange region. The reflectance curves in Fig. 3(b) indicate that the perceived color of each wafer is a mixture of all colors in the visible spectrum, weighted by the eye sensitivity, and are subjectively perceived by the HVS as turquoise, purple, and golden.

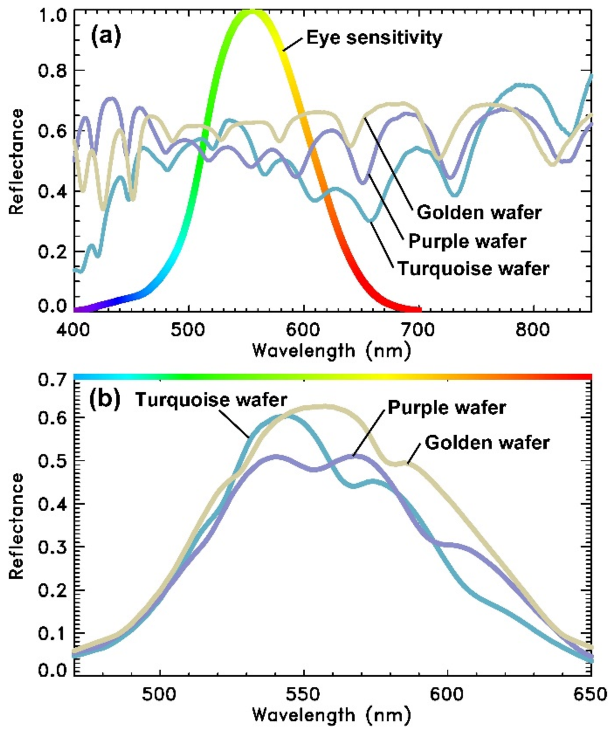

Fig. 3. (a) Measured reflectances of the wafers and the eye sensitivity and (b) the measured reflectances multiplied by the eye sensitivity.

3. Calculated SOI wafer reflectances

Reflectance calculations depend on the optical constants of the SOI wafer layers. In this paper, Si and SiO_2 optical constants from Palik's compilation [4] are utilized and are shown in Fig. 4. SiO_2 is transparent ($k = 0$) over the entire UV-VIS-NIR reflectance measurement range and has nearly constant refractive index $n = 1.5$. Si is transparent in the NIR and has changing n and k values at shorter wavelengths.

The reflectance code uses the formalism of [5] and calculates the complex Fresnel reflectivity and transmissivity coefficients at each layer interface and accounts for absorption in each layer. The reflectance code has been validated by numerous synchrotron radiation measurements ([6] and references therein).

The calculated reflectance of an Si wafer with 2 nm SiO_2 native oxide surface layer is shown in Fig. 5(a). The reflectance multiplied by the eye sensitivity is shown in Fig. 5(b). The reflectance varies smoothly across the VIS range, has rather low 0.37 peak value, and a Si wafer typically appears gray in color. Varying the thickness of the transparent SiO_2 surface layer has negligible effect on the visible reflectance.

The calculated reflectances of Si wafers with 2000nm and 2020nm thick SiO_2 surface layers are shown in Fig. 5(a). The reflectance curves have an oscillatory appearance in the UV-VIS-NIR range where SiO_2 is transparent. The SiO_2 layer functions as a lossless reflective Fabry-Perot

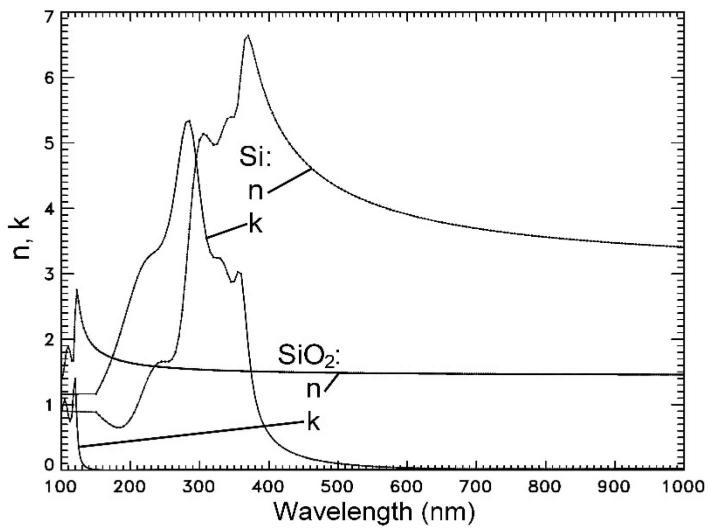

Fig. 4. Optical constants n and k of Si and SiO_2.

etalon resulting from the interference of the waves reflected from the top and bottom interfaces of the SiO_2 layer. The order number for destructive interference of the reflected radiation can be derived from the equation [7]

$$m = 2nT\cos\theta/\lambda + \varphi/\pi$$

where n is the refractive index, T is the layer thickness, θ is the angle of incidence, and φ is the change in phase at the two interfaces ($\varphi = 0$ in this case).

The destructive interference order values m in the VIS region are indicated in Fig. 5(b), where the wafer reflectance curves multiplied by the eye sensitivity are shown. The 20 nm difference in the SiO_2 layer thickness results in changes in the oscillation extrema wavelengths and changes in the perceived colors of the wafers. In effect, the changing SiO_2 thickness results in frequency modulation of the reflectance curve. The colors of Si wafers with surface SiO_2 layers can span the entire gamut of colors depending on the SiO_2 thickness.

The calculated reflectances of the three SOI wafers with varying Si surface layer thicknesses, multiplied by the eye sensitivity, are compared to the measured reflectances in Fig. 6. The thicknesses of the Si layers and the buried SiO_2 layers were varied in the calculation to match the measured reflectances.

The buried SiO_2 layer functions as a nearly lossless reflective Fabry-Perot etalon, and the assumed thickness of the buried SiO_2 layer primarily determines the wavelengths of the oscillation extrema seen in Fig. 6. Thin-film effects in the over-lying Si layer modulate the amplitudes of the oscillations, and the assumed thickness of the Si layer primarily determines the peak value of the reflectance.

In effect, the changing SiO_2 thickness frequency modulates the reflectance curve, and the changing Si thickness amplitude modulates the reflectance curve. Thus, the buried SiO_2 thickness and the Si thicknesses can be independently varied in the model to match the frequency and amplitude of the measured reflectance curve. The thickness of the SiO_2 surface layer had negligible effect on the calculated reflectance and was set to the 2 nm native oxide thickness.

By matching the calculated and measured reflectances for each wafer, the Si and buried SiO_2 layer thicknesses were determined and are listed in Table 1. The Si and buried SiO_2 layer thicknesses were 90 nm and 1950nm for the turquoise wafer, 45 nm and 2050nm for the purple wafer, and 30 nm and 2000nm for the golden wafer. The Si thickness decreased with etch time as

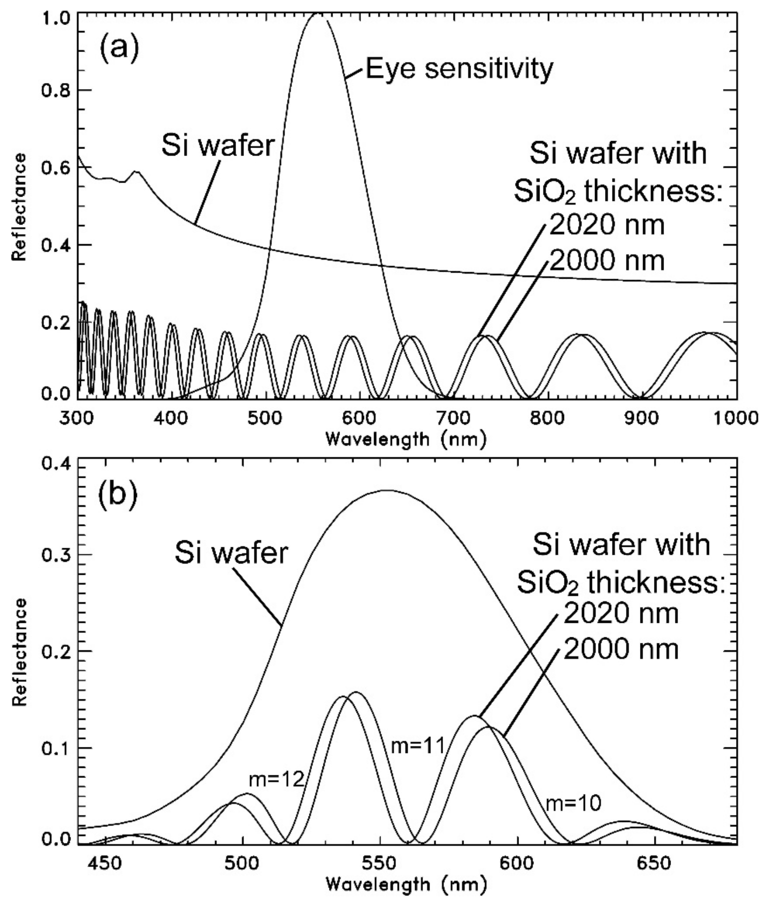

Fig. 5. (a) Calculated reflectance of a Si wafer with 2 nm native oxide and Si wafers with 2000 nm and 2020 nm thick SiO_2 surface layers. The eye sensitivity is also indicated. (b) Reflectances multiplied by the eye sensitivity. The number m refers to the destructive interference order of the reflectance from the top and bottom interfaces of the SiO_2 layer.

expected. The determined Si thicknesses are estimated to be accurate to ± 2 nm, and the SiO_2 layer thicknesses are accurate to ± 20 nm. The ± 50 nm (± 2.5%) variation in the buried SiO_2 layer thicknesses of the three wafers exceeds the ± 20 nm estimated accuracy of the measurement and likely results from variations in the SOI wafer fabrication process.

Table 1. SOI wafers with variable Si layer thicknesses

Layer	Turquoise Wafer (unetched)	Purple Wafer (etched 20 min.)	Golden Wafer (etched 40 min.)
Surface SiO_2 layer	2 nm	2 nm	2 nm
Si layer	90 nm	45 nm	30 nm
Buried SiO_2 layer	1950nm	2050nm	2000nm

The measured oscillation amplitudes are not as pronounced as in the calculated spectra, and this may result from the discrete interfaces assumed in the calculation, while the interfaces of the fabricated wafers could be more diffuse with mixed composition. In addition, the optical constants of the layers of the fabricated wafers may differ from the assumed Si and SiO_2 optical

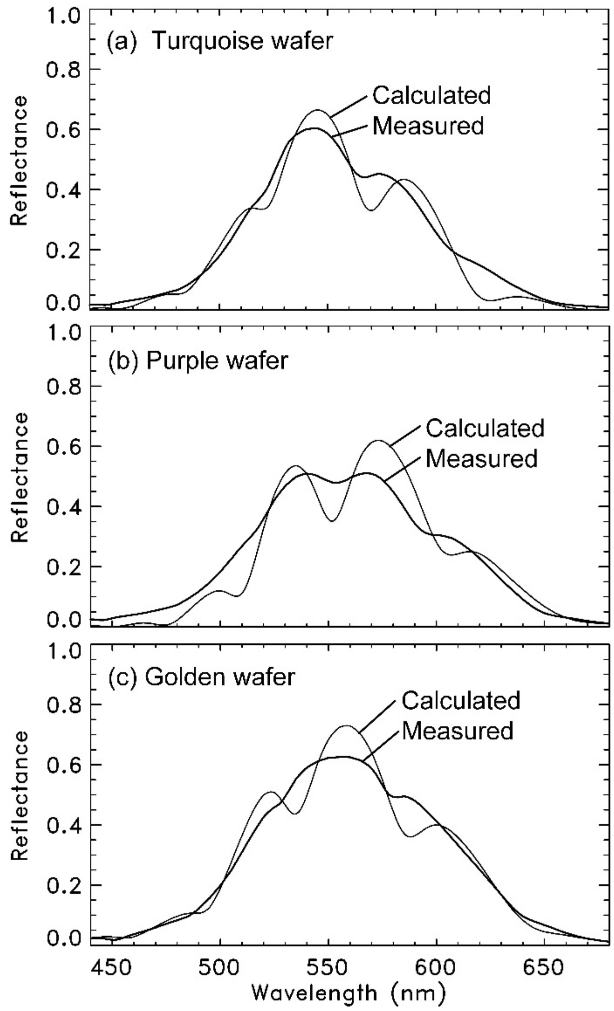

Fig. 6. Measured and calculated reflectances of the (a) turquoise wafer, (b) purple wafer, and (c) golden wafer.

constants from [4]. The agreement between the measured and calculated reflectances could be constrained by performing polarization-dependent measurements at multiple angles of incidence, as for traditional ellipsometry, but the present measurements are considered sufficient to explain the color variations of the etched SOI wafers.

4. CIE color calculations

In order to illustrate the gamut of SOI wafer colors resulting from variations of the Si layer thickness, the reflectances of SOI wafers with a fixed 2 µm buried SiO_2 layer, fixed 2 nm SiO_2 surface layer, and assumed Si thicknesses from 20 nm to 110 nm with 5 nm intervals were calculated. The CIELAB tristimulus values (L*, a*, and b*) were calculated from the calculated reflectance curves and assuming the CIE D65 2^o illuminant and observer [2]. The CIEUV color variation parameters u* and v* were calculated for each assumed Si layer thickness and are shown in Fig. 7. The calculated sRGB color is illustrated at each data point.

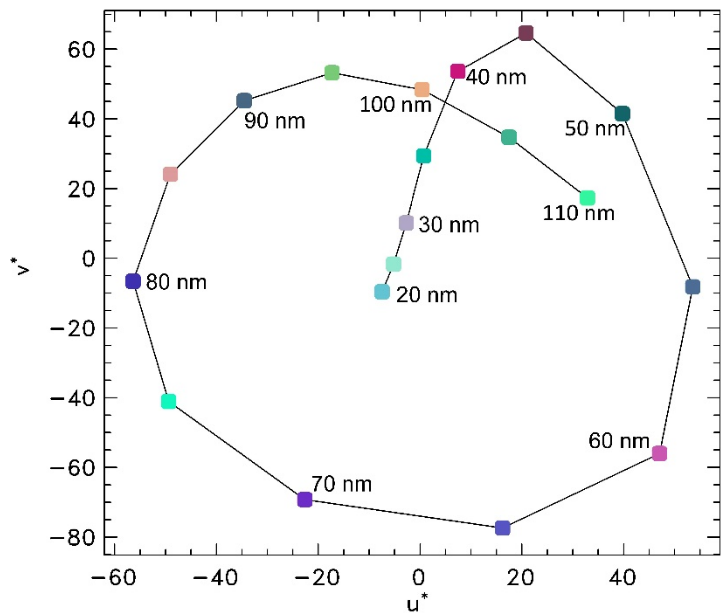

Fig. 7. Calculated values of the CIE color parameters u* and v* for SOI wafers with thin etched Si surface layers and a buried SiO_2 layer with 2000 nm thickness. The calculation is performed for Si thicknesses of 20 nm to 110 nm and at 5 nm intervals. The sRGB color of the wafer is illustrated at each data point.

It is apparent that the sRGB colors vary rapidly with Si layer thickness and change in an irregular manner across the visible spectrum. This is because, for each assumed Si thickness, the reflectance and sRGB values are mixtures of all visible colors, weighted by the spectral oscillations produced by the buried SiO_2 layer and modulated by thin-film effects in the Si layer, and the mixture of colors varies rapidly with Si layer thickness. In addition, different Si thickness can produce similar CIEUV (u* and v*) values and similar sRGB values, metamerism [2], and this means that the perceived wafer color may not uniquely determine the Si thickness.

Metamerism is most apparent in Fig. 7 where the u* versus v* curve intersects at Si layer thicknesses of 38 nm and 101 nm. Not only are the u* and v* values equal, but the CIELAB L* (lightness) values are nearly equal at these two Si thicknesses as shown in Fig. 8. Thus two SOI wafers having Si thicknesses of 38 nm and 101 nm have the same color and similar lightness and cannot be distinguished (metamerism). However, the changing colors of etched wafers with varying thicknesses and colors can in general be distinguished, and the changing colors can be useful initial indications of changes in the Si thickness during the etching process. The absolute values of the Si and buried SiO_2 layer thicknesses can be accurately determined by measuring and calculating the spectral reflectance of the wafer across the UV-VIS-NIR wavelength range.

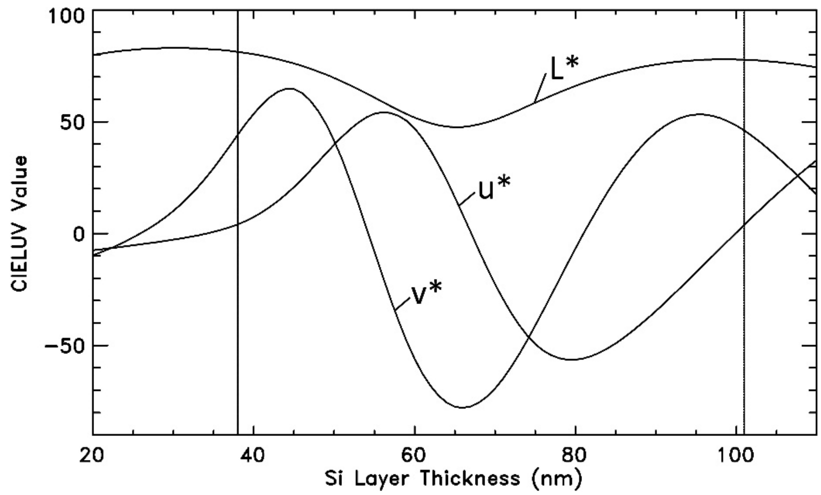

Fig. 8. Calculated values of the CIE color parameters u* and v* and the lightness parameter L* illustrating metamerism at the Si layer thicknesses 38 nm and 101 nm where the u* and v* values are equal.

5. Conclusions

It has been shown by UV-VIS-NIR spectral reflectance measurements and calculations that the perceived (by eye) color of an etched SOI wafer with a thin Si layer is a mixture of the oscillatory reflectance from the buried SiO_2 layer and thin-film effects in the Si layer. Changes in the Si thickness in the range 90 nm to 30 nm result in significant changes in the perceived color, from turquoise to purple to golden.

By comparing the measured and calculated reflectances, the buried SiO_2 thickness is determined from the frequency modulation of the reflectance curve, and the Si thickness is independently determined from the amplitude modulation of the reflectance curve. Using the specular reflectance measured at 10^o angle of incidence, the Si thickness and the buried SiO_2 thickness can be determined with estimated accuracies of ± 2 nm and ± 20 nm, respectively.

CIE u* and v* color parameter values, calculated for Si thicknesses from 20 nm to 110 nm, span the entire gamut of colors. Changes in the perceived colors of etched SOI wafers are useful for evaluating the Si thickness in real time during the etching process. The absolute Si and buried SiO_2 thicknesses can be accurately determined by comparisons of the measured and calculated reflectances.

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Disclosures. The author declares no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the author upon reasonable request.

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