Thickness Estimation of Silicon-on-Insulator By Means of the Fourier Transform of Bilinearly Transformed Infrared Reflectance Data

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Knowledge of film thickness is essential for device design in silicon-on-insulator technology. A new thickness estimation technique, based on the calculation of the spatial frequencies of bilinearly transformed infrared reflectance data in a spectral window, is introduced. The assignment of dominant spectral peaks in the power spectral density curve to the optical thickness of the silicon, silicon dioxide and the combined layer, is also presented. Examples for silicon-on-silicon dioxide with the silicon layer ranging in thickness between 1000 nm and 50 nm, with fixed oxide thickness, are presented. Thickness values of both layers to better than a few percent accuracy, were obtained for silicon layers down to 100 nm and with reduced accuracy for layers as thin as 50 nm.

Key words: Non-destructive testing, infrared reflectance spectroscopy, thickness estimation, silicon-on-insulator

I. INTRODUCTION

Silicon-on-insulator technology holds promise in the areas of high speed, radiation hard integrated circuits, integrated optics and sensors. Information regarding the semiconductor film and the buried insulator thickness is essential for device design in this technology. The appropriate layer thickness varies according to the particular application, and may range from ultra-thin to relatively thick.

Recently, as lateral device dimensions have been reduced, the trend has been towards the use of much thinner layers for MOSFET's. Device properties on these thinner layers can also be improved. For instance, the use of thin and ultra-thin, fully depleted SOI films eliminates detrimental floating body effects such as the kink-effect. In addition, sharp subthreshold slope, increased transconductance, and reduced short-channel effects are possible. In order to manufacture and study devices with these desirable properties, it becomes essential to be able to measure the film thickness accurately over the range from approximately 50 to 300 nm.

On the other hand, SOI material is also beginning to receive attention in the field of integrated optics. In this particular application light is guided in the higher indexed silicon film sandwiched between two layers of SiO₂. The silicon thickness in this instance ranges between 200 and 2000 nm.

In both the IC and the optical applications, the thickness of the SiO₂ layer varies between approximately 350 and 1000 nm.

Therefore a need arises for the non-destructive determination of both the silicon and the insulator thickness at the wafer level. Some form of optical interferometry will satisfy the needs of speed and non-destructiveness. Silicon-on-insulator, however, presents special problems complicating the issue. For instance, the SOI material is a double layer structure with layers that can be relatively thin or relatively thick and refractive indices that are wavelength dependent.

Kamins and Colinge proposed a technique whereby the thickness of both the silicon surface layer and the insulator can be determined non-destructively. The method compares the positions of the minima in the optical reflectance pattern measured in the visible to minima obtained by a simulation of the reflectance. Their technique requires the wavelength dependent complex indices of refraction for the semiconductor and the insulator in the visible region of the spectrum. The use of the method either requires a large amount of computer time, or it requires a nomograph for each different insulator thickness.

A possible alternative solution could be provided by differential reflection spectroscopy. In this technique one measures the wavelength dependence of the normalized difference between the reflectivities of two samples which are placed side by side. It is very sensitive to small changes in the reflectance of the two specimens, and it is most suitable for quality control where a standard SOI reference would be used for comparative purposes. However, the analysis of arbitrary samples will be quite involved, for it requires the analysis of the interference fringes in a differential spectrum where the parameters of two layers could be varying.

We will present a technique which uses very little computer time, and requires only average values of the real part of the refractive indices of the semiconductor and insulator.
II. THEORY

2.1 Relationship Between Fourier Spectrum and Film Thickness

Properly processed silicon-on-insulator material can be modelled optically as a double layer structure on a substrate. Reflectance under normal incidence at the wavelength \( \lambda \) is given by

\[
R(\lambda) = \frac{A + f(\theta_1, \theta_2)}{F + f(\theta_1, \theta_2)}
\]

where

\[
f(\theta_1, \theta_2) = a_1 \cos 2\theta_1 + a_2 \cos 2\theta_2 + a_3 \cos 2(\theta_1 + \theta_2) + a_4 \cos 2(\theta_1 - \theta_2)
\]

and

\[
A = r_1^2 + r_2^2 + r_3^2 + r_1^2 r_2^2 r_3^2
\]

\[
a_1 = 2r_1 r_2 (1 + r_2^2)
\]

\[
a_2 = 2r_2 r_3 (1 + r_1^2)
\]

\[
a_3 = 2r_1 r_3
\]

\[
a_4 = 2r_1 r_2^2 r_3
\]

\[
F = 1 + r_1^2 r_2^2 + r_2^2 r_3^2 + r_2^2 r_3^2
\]

The \( r_j \)s denote the individual Fresnel reflectances of the three interfaces and are given by

\[
r_j = (n_{j-1} - n_j)/(n_{j-1} + n_j), \quad j = 1, 2, 3
\]

\( \theta_1 \) and \( \theta_2 \) are the phase thicknesses of the silicon and insulator layers, respectively, and are given by:

\[
\theta_j = 2\pi n_j d_j/\lambda, \quad j = 1, 2
\]

By expanding the denominator in a power series, the reflectance may be written as

\[
R(\lambda) = R_0 \sum_{n=0}^{\infty} k_n f^n(\theta_1, \theta_2)
\]

where the \( k_n \) are functions of the individual Fresnel reflectances of the three interfaces. Consider the first term in the expression for \( f(\theta_1, \theta_2) \):

\[
a_1 \cos 2\theta_1 = a_1 \cos \left[ 2\pi \cdot 2n_1 d_1 \cdot \frac{1}{\lambda} \right]
\]

\[
= a_1 \cos \left[ 2\pi \cdot d'_1 \cdot \frac{1}{\lambda} \right]
\]

where \( d'_1 = 2n_1 d_1 \) = optical thickness for a wave traversing the layer of refractive index, \( n_1 \), twice. If expressed as in Eq. (7), the optical thickness is analogous to frequency, and the inverse wavelength analogous to time in the language of conventional Fourier analysis. The data therefore contains several "frequency" components corresponding to \( d'_1, d'_2, (d'_1 + d'_2), 2d'_1, 2d'_2, 2(d'_1 + d'_2), \) etc.

As an illustration, the calculated reflectance pattern of an ideal SOI-structure consisting of a silicon film with a thickness of 750 nm and a silicon dioxide layer, 1000 nm thick, on top of an infinitely thick silicon substrate, is presented in Fig. 1(a). The refractive indices were assumed to be real, wavelength independent, with values of 3.42, 1.45 and 3.42, respectively. The digital Fourier transform of the reflectance is presented in Fig. 1(b). As is to be expected from Eqs. (6) and (7), numerous frequency components are present, thus complicating the assignment of optical thickness to "frequency."

Fig. 1(a) — Calculated reflectance pattern of an ideal SOI-structure with \( d_1 = 750 \text{ nm} \) and \( d_{\text{SiO}_2} = 1000 \text{ nm} \) on an infinitely thick silicon substrate (no dispersion).

Fig. 1(b) — The digital Fourier transform of the calculated reflectance pattern given in Fig. 1(a).