Model-based infrared reflectometry for measurement of high aspect-ratio through-silicon vias

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The non-destructive and high throughput measurement of etched depth and profile in the fabrication of through-silicon vias (TSVs) is critical for the process control in the three-dimensional integrated circuit technology. In this paper, we introduce the model-based infrared reflectometry (MBIR) and investigate its capability for the measurement of TSV depth and profile with a simulated study. We propose a combined method with Fourier transform (FT) analysis and Levenberg–Marquardt (LM) algorithm for robust and fast extraction of geometric parameters from the measured reflectance spectrum. The simulated results demonstrate that the MBIR is an adequate candidate for the metrology of TSV structures, and it is expected to provide a useful tool for the process control in the fabrication of etched TSVs.

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1. Introduction

Currently, three-dimensional cell stacking and chip stacking can be implemented through various integration schemes such as the through-silicon via (TSV) interconnects, which offer several advantages [1]. In the fabrication of etched TSVs, non-destructive and high throughput measurement of etched depth is critical to allow timely feedback for process control, process development, and the prevention of process excursions in three dimensional integrated circuit process technology. Recently, an infrared optical metrology, in terms of the model-based infrared reflectometry (MBIR) has been developed and already been exploited in applications for submicron deep trench in dynamic random access memory [2]. In this paper, we introduce the MBIR for the measurement of TSV structures and intend to investigate its capability with a simulated study. To apply the MBIR in the metrology of TSV structures, one of the key issues is how to extract the via parameters from the measured data accurately and quickly. We propose a Fourier transform and Levenberg–Marquardt (FT-LM) combined method, in which the FT analysis is used to generate an initial estimate of the via width and depth, and the accurate result is finally obtained by the LM algorithm.

2. Methods

In the reflectance spectrum of TSV structures, we notice that the oscillation component is regular in the lower wavenumber range, i.e., in the higher wavelength range. The amplitude and frequency of the regular oscillation component are found to be proportional to the via width and depth. Therefore, we propose an FT analysis based method to directly calculate an initial estimate of the via width and depth from the reflectance spectrum. Then the accurate result is obtained by the LM iteration with the initial estimate provide by the FT analysis. The flowchart of parameter extraction with the FT-LM combined method is shown in Fig. 1.

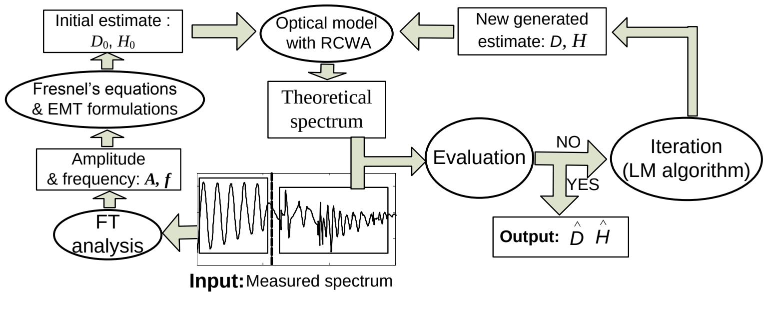

Fig. 1 Flowchart of parameter extraction using the FT-LM combined method.

Firstly, the measured reflectance spectrum of the TSV structure is divided into two parts by the diffraction threshold, which in wavelength is about 5 times of the TSV pitch. The FT analysis is performed to the left part of the reflectance spectrum, and the amplitude A and frequency f of the regular oscillation component in the lower wavenumber range are obtained. Then, the via width and depth are analytically calculated from the obtained amplitude and frequency with the Fresnel's equations and the EMT formulations [3], resulting in an initial estimate of the via width D_0 and depth H_0. Finally, the accurate measurement result of the via width D and depth H is achieved by the LM algorithm after several iterations, with D_0 and H_0 as the initial estimate. We choose the spectrum at the right side of the diffraction threshold for the LM algorithm and use the RCWA method for the accurate optical modeling, since the EMT is no longer applicable in this higher wavenumber range.

3. Stability evaluation of the FT-LM combined method

To evaluate the stability of the FT-LM combined method for the extraction of via parameters in MBIR, we carried out some simulations on 20 test samples. The via pitch of the samples varies from 1 to 3 μm with a fixed fill factor of 0.5, and the via depth varies from 15 to 30 μm. Figure 2 (a) and (b) depict the extracted results in the FT analysis step and in the final step with the LM method. The excellent test results demonstrate that the FT analysis based method can provide a robust initial estimate for solving this inverse spectral problem.

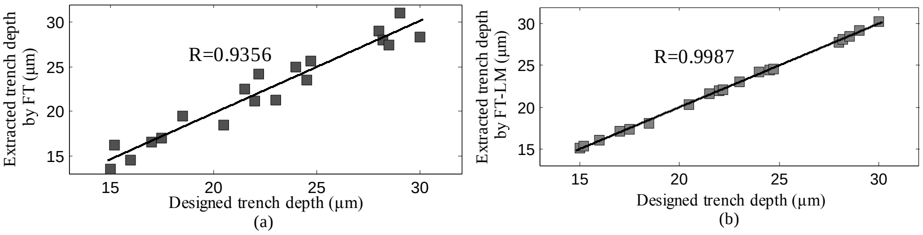

Fig. 2 The extracted results of via depth by (a) FT analysis based method, and (b) the FT-LM combined method.

4. Application in metrology of a typical TSV structure

In order to evaluate its applicability for measurement of an actual TSV structure, we further apply the FT-LM combined method in the parameter extraction for MBIR through a simulation test. As shown in Fig. 3(a), the TSV structure consists of a hard mask layer on the high aspect-ratio via layer. The depth of mask layer and via layer are designed to be 0.5 μm and 30 μm, respectively, the via pitch is 2 μm, and the CD is 1 μm. The refractive index of the mask is set to be 2, and the refractive index of the substrate is set to be 3.4 in the mid-infrared wavelength range. The simulated spectrum with RCWA is considered to be the "measured data", as shown in Fig. 3(b). The extracted results are shown in Table 1. It is observed that only a rough initial estimate of the via width and depth in the FT analysis step can be achieved, with the relative errors of 13.5% and 5.8%, respectively. This is due to the spectral leakage of the FT analysis and the deviation of the EMT modeling. However, this rough initial estimate could lead to the final solutions with much lower relative errors of 0.17% and 0.23% for the via width and depth, respectively.

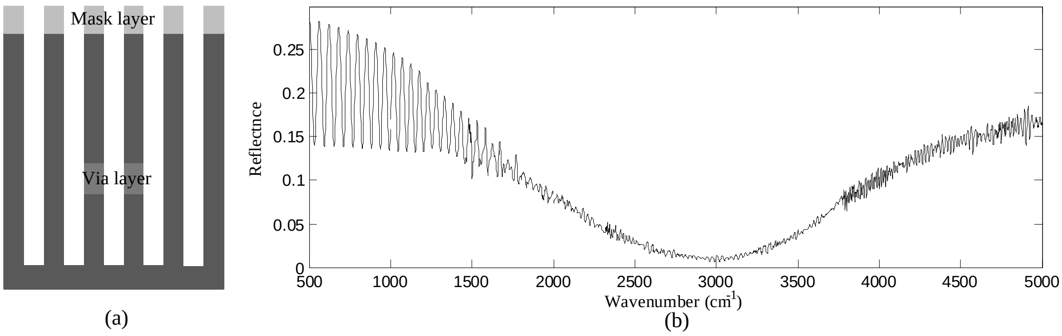

Fig. 3 (a) A typical TSV structure, and (b) its reflectance spectrum as the "measured data".

Methods	Via Width		Depth of mask layer		Depth of via layer	
	Error(nm)	Relative error	Error (nm)	Relative error	Error (μm)	Relative error
FT	135	13.5%			1.75	5.8%
FT-LM	1.7	0.17%	2.38	0.48%	0.07	0.23%

Table 1 Comparison of the extraction errors by the FT analysis based method and the FT-LM combined method.

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