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Exploring the reconstruction of a finite dielectric frustum-shaped object by the parametrized spatial spectral volume integral equation

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Summary. Soft X-ray scatterometry has the potential for sub-nm and three-dimensional profiling of integrated circuits, but the associated scatterometry measurements are prone to low signal-to-noise levels. We extend a two-dimensional parametrization framework of an accurate and noise-robust inverse-scattering method for three-dimensional finite dielectric objects, to include a three-dimensional parametrization in the form of a sidewall-angle extension. This is tested against synthetic inverse scattering data under high-noise conditions.

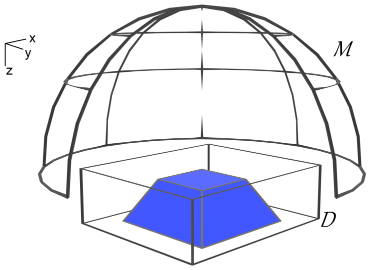

Fig. 1. The geometrical setup for the reconstruction of the finite (blue) object.

1 Introduction

To improve the storage capacity of memory devices, next-gen integrated circuits (ICs) have feature sizes of mere nanometers [1]. Consequently, wafer metrology techniques have to perform three-dimensional (3D) profiling of key features of ICs, e.g. sidewall-angle, with sub-nm accuracy to ensure a reliable and cost-effective production process. A promising technique is soft X-ray (SXR) scatterometry, since it has the potential of sub-nm profile monitoring owing to its wavelength range of 10 up to 20 nm [2]. Moreover, most materials are near-transparent at SXR's wavelength, which enables 3D monitoring of the ICs. However, accurate 3D profiling by SXR scatterometry is difficult, due to current technological limitations in SXR sources that induce poor signal-to-noise ratios (SNRs).

In [3], an inverse-scattering method demonstrated the noise-robust reconstruction of 3D finite dielectric objects, while using synthetic scatterometry data with phase information. The method consists of a Gauss-Newton method with a frequency-domain Maxwell solver based on Gabor frames, i.e. the spatial spectral volume integral equation (VIE) [4]. Further, each object is described by a consistent, parsimonious and continuously differentiable parametrization of its polygon-shaped cross-section. By combining this parametrization with the employed Gabor frames, the spatial spectral VIE's linear system is continuously differentiable with respect to the parametrization. Consequently, the geometrical parameters of several objects are retrieved with errors smaller than a tenth of the wavelength, even at a SNR of 3 dB. Moreover, this reconstruction did not require any bounds on the parameter values or other forms of regularization. Hence, this method provides accurate and noise-robust reconstruction for structures with a uniform cross-section along their height.

However, the 2D nature of the parametrization used in [3] is inadequate for 3D features of ICs. Although literature contains solutions for the parametrization of structures with variations in all three dimensions, e.g. [5, 6], the resulting parametrization typically hinges on user-imposed bounds on the parameter values to enforce a physically possible configuration. Hence, there is a clear need for a consistent and parsimonious parametrization such that inverse-scattering methods can robustly and accurately reconstruct the parts of an IC with variations in three dimensions, without further input from a user.

As a first step towards such a full 3D parametrization, we propose a consistent sidewall-angle extension of the parametrization in the noise-robust inverse-scattering method of [3], to accurately reconstruct a 3D finite dielectric object such as a frustum in synthetic and noise-contaminated SXR scatterometry experiments.

2 Geometrical description

Fig. 1 displays the geometrical setup with Cartesian coordinate system in this work. A finite dielectric frustum-shaped object is contained in a wire-frame box, which represents the computational domain $\mathscr{D}$ with dimensions $[-W_x, W_x] \times [-W_y, W_y] \times [z_{min}, z_{max}]$.

The electromagnetic responses of the object are measured on domain $\mathscr{M}$, which is a half-sphere here. Further, domain $\mathscr{M}$ is placed at a sufficiently large distance from domain $\mathscr{D}$ such that the inverse-scattering method operates on the object's far-field response. For both domains, we assume that the background medium is vacuum ($\varepsilon_r = 1$).

3 Parametrized frustum-shaped objects

Here, a 3D finite frustum-shaped dielectric object is defined as a locally homogeneous contrast function, which occupies the domain $\mathscr{D}_s$, which is a subdomain of $\mathscr{D}$. This contrast function is only non-zero and equal to $\chi(\mathbf{x}_t,z) = \varepsilon_r^s - 1$ when $(\mathbf{x}_t,z) \in \mathscr{D}_s$, with $\mathbf{x}_t = (x,y)$ and ε_r^s is the object's relative permittivity. The contrast function's shape is formed by the vertices of the two polygon-shaped base faces of the frustum-shaped object. These vertices are the parameters of the object. We define the vertices of its base faces at $z = z_{min}$ and $z = z_{max}$ as $\mathbf{x}_i^b = (x_i^b, y_i^b)$ and $\mathbf{x}_i^t = (x_i^t, y_i^t)$, respectively, with $i = 1,2,\ldots,L_s$. We connect the vertices $\mathbf{x}_i^b$ and $\mathbf{x}_i^t$ as $\mathbf{x}_i^s(z) = \mathbf{x}_i^b + (\mathbf{x}_i^t - \mathbf{x}_i^b)[(z - z_{min})/(z_{max} - z_{min})]$.

To obtain a continuously differentiable linear system for the spatial spectral VIE with respect to the parameters, the contrast function needs to be expanded in Gabor frames in the transverse plane $\mathbf{x}_t$ for $z_{min} \leq z \leq z_{max}$. For objects with a uniform polygon-shaped cross-section, a method is given in [3], based on the transverse Fourier transform of that cross-section. For a frustum, one needs replace the variable $\mathbf{x}_i^s$ in [3, Eq. (16)] by $\mathbf{x}_i^s(z)$ as introduced above. This yields

$$\chi(\mathbf{k}_t,z) = -\sum_{i=1}^{L_s} \frac{j\mathbf{k}_t^{v}\cdot\mathbf{d}_i(z)}{(\varepsilon_r^s-1)^{-1}}\,\frac{e^{j\mathbf{k}_t\cdot\mathbf{x}_i(z)}\left(e^{j\mathbf{k}_t\cdot\mathbf{d}_i(z)}-1\right)}{j(\mathbf{k}_t\cdot\mathbf{k}_t)\,[\mathbf{k}_t\cdot\mathbf{d}_i(z)]},$$

with the spectral arguments $\mathbf{k}_t = (k_x,k_y)$ and $\mathbf{k}_t^v = (-k_y,k_x)$, and the vectors $\mathbf{d}_i(z) = \mathbf{x}_{i+1}^s(z) - \mathbf{x}_i^s(z)$ that connect points on the frustum's edges at equal z. With this adaptation, the first-order partial derivatives of the parametrized contrast function maintain the form as in [3, Eq. (18)]. Hence, the existing inverse-scattering method then also applies to the reconstruction of a frustum.

4 Parameter reconstruction results

The contrast function of the frustum-shaped object is visualized in Fig. 2 by its two parametrized base faces in the form of gray polygons. This dielectric object is further defined by $\varepsilon_r^s = 1.2$, while $z_{min} = 0$ nm, and $z_{max} = 12$ nm. We used the finite element method of Altair's FEKO, to generate independent reference far-field data at a wavelength $\lambda = 15$ nm. This reference data is contaminated by Gaussian noise with a SNR of 0 dB. Fig. 2 also displays the progression of the parameter reconstruction results by the inverse-scattering method. The initial estimate values for the geometrical parameters are based on the application of a small random Gaussian perturbation of $\mathscr{N}(0, 0.2\lambda)$ per parameter, which reflects the typical situation with high-quality prior knowledge in wafer metrology. The largest absolute reconstruction error is 0.35 nm, i.e. the y-coordinate of the small polygon's bottom left vertex. Overall, the extended parametrization in combination with the spatial spectral VIE facilitates the accurate and noise-robust reconstruction of an object with variations in all three spatial dimensions as a result of a sidewall-angle.

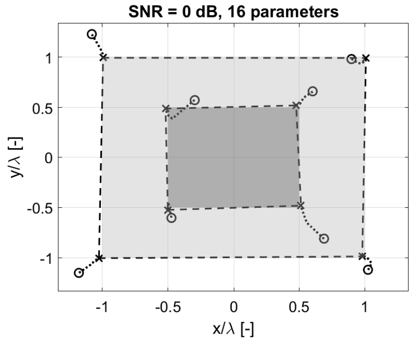

Fig. 2. The circular and cross markers display the initial and final estimation of the parameter values by the Gauss-Newton method, respectively. The dashed line segments show the progression of the Gauss-Newton method per parameter. The cross markers are connected by line segments, to visualize the reconstructed shapes of the base faces.

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