Development of the Method of Electron—Optical in Situ Monitoring for Periodic Structures

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Abstract—A series of the basic problems for the development of the method of electron—optical in situ monitoring for periodic structures are considered in this work. In particular, the problem of submicron- and nanosized inhomogeneity online monitoring in large areas of tested microelectronic structures with a typical size of the order of 100 μm is discussed to give individual inhomogeneities in detail. The Riccati equation method has been proposed to solve the problem.

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1. INTRODUCTION

A combination of optical reflectometry [1] and electron microscopy will probably allow one to develop an efficient method of in situ monitoring for submicron- and nanosized inhomogeneities in large areas of tested microelectronic structures with a typical size of the order of 100 μm to give individual inhomogeneities in detail. One can note that at least two known examples with a tendency to combined application of electron and optical microscopy exist. Control of the shape perfection of ribbon diffraction gratings with different profiles on the integral optoelectronic structure is based on analysis of an optical image in a far-field region that is preliminarily calibrated using data of electron or atomic force microscopy [2]. According to another approach [3], distortions caused by electron lenses forming an image with the required magnification are eliminated by virtue of fixation of the front of electron waves scattered from the object at a screen and subsequent reproduction of the diffraction pattern in the form of a light-wave front (the Gabor method [4]). The problem of integration of informative possibilities of classical (visible light) and quantum (electron) wave fields is posed in the present work for microscopy without a priori information and additional sources of coherent light.

2. OPTIMIZATION OF ELECTRON-BEAM SYSTEMS FOR MONITORING OF PERIODIC STRUCTURES

The approach to the problem of monitoring of periodic structures is formed by the following. The most advanced methods for solving the problem of the size control of VLSI elements during their production are those of scanning electron microscopy. In this case it is necessary to develop linear measures of micron, submicron, and nanometer ranges with an error of measurements of 3–5% relative to the design rules of the critical sizes of VLSI elements from 115 to 22 nm. Correspondingly, the resolution of the method should be units of nanometers.

In spite of the fact that scanning electron microscopes (SEMs) with a resolution better than 1 nm have appeared in the last years, their practical use for monitoring of rather large areas (larger than 1 cm$^2$) is running into a series of problems [5]. The most substantial limiting factor is the method itself of step-by-step image construction in SEM, at which a linear decrease in the image element (resolution enhancement) leads to quadratic increase in the monitoring time of the investigated surface. For example, the time of full scanning of the surface 1 cm$^2$ in area for the beam diameter of 3 nm and the duration of exposure of one image element (pixel) of 5 ns is about 14 h. In addition, it is necessary to take into account the statistical character of the signal formation and the possibility of electron beam damage of the object. Detailed analysis of these factors results in the conclusion that the duration of pixel of 5 ns is minimally attainable and, consequently, the combination of the efficiency and SEM resolution in the mode of structure monitoring for the above-mentioned example is close to the limiting one.

Thus, it is necessary to use additional—in particular, optical—methods for monitoring rather large areas. It will allow one, on the one hand, to obtain additional information on the parameters of periodic structures and classify them and, on the other hand, to realize the selective detailed scanning of individual areas. Thereby, the monitoring time can probably decrease more than one order of magnitude on retention of statistically reliable results.
3. REFLECTOMETRY
IN A FAR-FIELD REGION

Periodic step-by-step (ten of periods) and single relief structures on a surface of solid are currently used as linear measures in the practice of linear measurements in SEM. Errors take place in the technology of preparation of these measures. For example, a slope angle of a lateral trapezium face and a trapezium height can strongly change during the preparation of a step-by-step structure with a trapezoidal profile consisting of SiO$_2$ strips on Si 3017 ± 5 nm in period and $h = 356 ± 1$ nm in height, or the angles of upper asperity can become smooth. The problem of reflectometry is to determine a fraction of incident energy reflected into the specular order, into the non specular but uniform order, or into the nonuniform spectral order, as the period and height vary or the grating profile is angularly smoothed. The non-uniform modes are interesting because they do not remove the energy of the incident field from the grating and, consequently, AFM in the mode of near-field optics can give information on the grating structure in principle in a submicron scale. The Riccati equation method [6] is used to solve the assigned task. The approach [6] allows us to develop a monitoring method not only for one-dimensional structures (Fig. 1a), but also for structures with three-dimensional integration of elements (Fig. 1b) and even for the case of small dielectric contrast between the material of elements and the surrounding matrix.

3.1. Reflection Spectra of 1D and Combined Gratings

It is known from the literature [7] that the reflection efficiency of the TE polarized wave from the diffraction grating can change in resonance for the specified values of the grating spacing or the depth of its profile. In particular, the resonance reflection increase, as well as so-called perpendicular Wood anomalies [8], also known as Rayleigh-type anomalies, has been calculated in [9] for the standard diffraction grating (Fig. 1a, $L_0 \rightarrow \infty$). In the case of a non-zero value of the electric vector component normal to the undisturbed surface, the anomalies of the reflection coefficient are considered to be associated with excitation of the incident wave in the grating of surface plasmons [10]. In the case of TE polarization, the Rayleigh-type anomalies are physically caused by mutual transformation of uniform and nonuniform waves upon their multiple scattering from the grating under the condition that the absolute value of the component k of their wave vector k proves to be the wave number $k_0$ of the wave in a free space, i.e., to be the condition $k = 0$. Here the $x$ component of the vector k is denoted by $k^x_{\mu} = k_{0x} + 2\pi \mu / \Lambda$, $k_{0x} = -k_0 \sin \alpha$, and $\alpha$ is the angle of incidence of the wave.