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Flatbed scanner as an instrument for physical studies

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Abstract

A new method for nondestructive testing of the optical properties of various materials (semiconductors, dielectrics and metals) has been presented. It is based on the determination of geometric and optical inhomogeneities of the objects using the measurement data on the objects characteristics of the light scattered by them. It has been proposed to use a flatbed scanner as a physical device for measuring the scattered light. An analysis of the method possibilities showed that it is possible to measure the roughness and surface curvature, identify single defects on the surface, to measure the electrophysical parameters of materials being transparent in the visible region of the spectrum by means of the scanner. The method is simple to implement, it is on par with the accuracy of measurements made with many specialized physical devices, it is superior to the expensive equipment in a body of on-line information, it makes testing material properties under production conditions possible.

Keywords: Flatbed scanner; Light scattering; Geomrtrical and optical inhomogeneities; Surface roughness.

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1. Introduction

The search for objective methods of non-destructive testing and the development of rapid methods for assessing the quality of semiconductors and other materials used in electronics is of interest both for research purposes and for production.

Gorokhov et al. [1] discussed combining a flatbed scanner with modern information technologies for the rapid assessment of silicon carbide crystal properties. This concept was further implemented by the original methods of testing the properties of various materials of electronic equipment that we have developed by now [2–4]. These methods ensure a contact-free, non-destructive way of controlling the material properties which, combined with unorthodox approaches to using modern computer equipment, makes for greater accessibility and reduced costs.

The goals of the present work are to justify the concept and the physical basics of the method of studying the properties of the materials of electronic equipment using a flatbed scanner as a key measurement device, to compare the method to other existing techniques, to discuss the equipment necessary for implementing the method and its possible applications, and to demonstrate some of the results obtained.

2. The concept and the physical basis of the method

We can safely claim that any differential method is a reliable measurement method, especially if the

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measurements are performed not with respect to the reference signal, which itself is a source of error, but relative to “pure zero”. For example, the scattered light method, with the states of absolute transparency and absolute specular reflection serving as signal “zeros”, is used in optical measurements. This method can be implemented with commercially available flatbed scanners.

A flatbed scanner due to the peculiarities of its optical system does not “see” the mirror surface and therefore is an ideal physical instrument for recording the scattered light reflected by plane objects in the visible wavelength range.

Before describing various scanners and their properties, let us discuss briefly the scattered light method.

The objects around us reflect light. The reflected light contains diffused and specular/reflective components. The ability to see objects depends on these two components. Fig. 1 schematically shows how the human eye sees the real world (Fig. 1a) and how it would be seen if the objects around us were purely specular/reflective, and the atmosphere would be completely transparent (Fig. 1b).

Interacting with the solid matter of different objects, the light creates a visual image of the object due to the scattered light whereas the spectral composition of the scattered light carries information about the optical properties of the solid matter. Light scattering is determined by the geometric and optical in-homogeneities of reflecting items. The more heterogeneous the object, the greater the scattering intensity is. Let us briefly consider the nature of the inhomogeneities of the objects that can cause light scattering.

Geometric inhomogeneities include the surface roughness of the studied object. Measuring the intensity of light scattered by a rough surface allows to estimate the magnitude of the roughness, the homogeneity of the relief of a ground or a polished surface, and the presence of major defects.

The optical properties of the medium are characterized by a complex refractive index. The variability of this parameter throughout the bulk of the studied object means that it is optically inhomogeneous and leads to the scattering of the radiation falling on the object.

Optical inhomogeneities of the studied medium may include second-phase inclusions, or chemical composition inhomogeneities such as inhomogeneity of the solid solutions of semiconductors and other materials. Photonic crystals are a striking example of regular optical inhomogeneities. The characteristics of scattered radiation can give clues about the concentration, shape and orientation of scattering centers and about their spatial and size distribution.

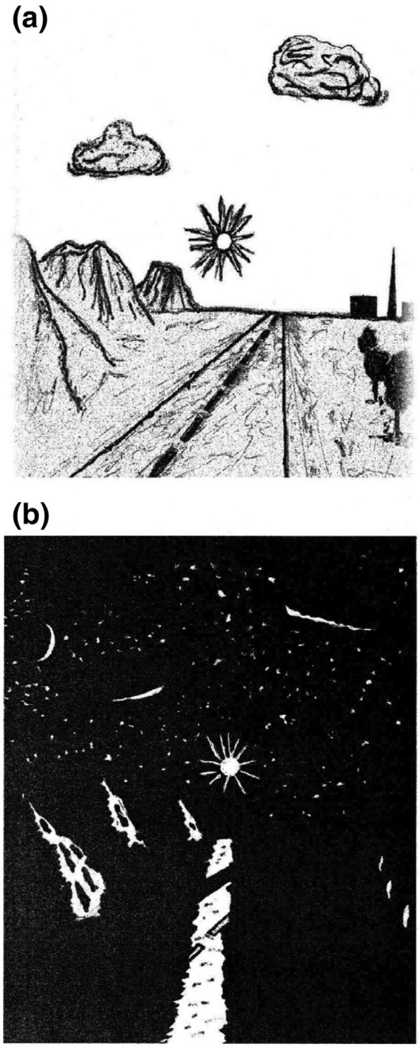

Fig. 1. The visual perception of the same landscape in a real (a) and a completely specular (b) world.

It follows from the above that this concept is not new, and the study of scattered light intensity and spectral composition was used multiple times for researching the properties of various materials and media. The problem with the currently existing measurement methods and the experimental equipment necessary for implementing them are rather complicated and expensive.

3. Flatbed scanner as a device for recording scattered light

A modern scanner [5–7] consists of two functional parts: the scanning mechanism and the software

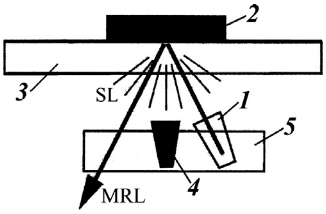

Fig. 2. Layout of the flatbed scanner elements (without the optical system elements): 1 – light source, 2 – object, 3 – fixed glass, 4 – photodetectors, 5 – scanner carriage; SL and MRL are the scattered and the specularly reflected light, respectively.

(TWAIN-module). A scanned object is located on a fixed transparent glass. A carriage with the light source and the line of photo detectors (CCD–CCD elements or phototransistors) is moving along and over the fixed glass. The optical system of the scanner projects light beam from the object to the photo detectors where information is separated by color. Photodetectors convert the light level into the voltage level. Next, the analog signal arrives to an analog-to-digital converter (ADC) that outputs the information in binary code. Then the information is processed in a scanner controller and is input into a TWAIN-module, i.e. a scanner driver that interacts with computer applications.

The geometry of the optical system of the scanner is such that the light that is specularly reflected from the sample does not reach the photodetectors (Fig. 2), so the scanner can be used as a physical instrument for recording the scattered light.

A flatbed scanner that is a relatively easy-to-use device for reading images and texts from printed materials can serve as an excellent tool to obtain and subsequently analyze object images, i.e., for contactless non-invasive diagnostic scanning.

Let us emphasize the value of the scanner as an instrument for physical research:

1. The scanner is a complete experimental setup for observing the scattered light from the flat objects in the visible wavelength range;
2. The scanner has ‘‘flat’’ optical characteristics as opposed to devices with spherical or cylindrical optical systems (cameras, video cameras, microscopes and so on.) This allows to eliminate the errors arising from controlling the uniformity of the properties of studied flat objects;
3. A non-contact scanner reads/scans the information ‘‘line by line’’ in contrast to the serial line reading in most contact scanning technologies of various modern microprobe methods (such as profilers and various scanning microscopes, e.g., an electron tunneling or an atomic force microscope) [8], which provides for high-speed data collection from large-area objects and allows to register and handle large amounts of information;
4. The scanner can provide high accuracy measurements for random error variables.

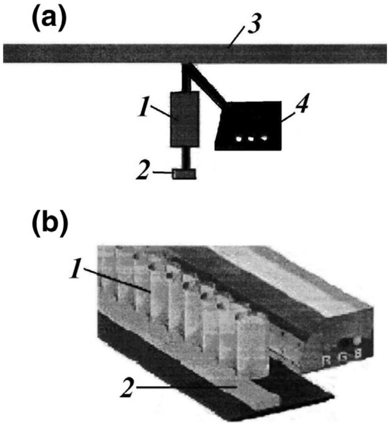

Fig. 3. A LIDE scanner layout (a) and a line of photosensitive elements (b): 1 – cylindrical lenses, 2 – a phototransistor array, 3 – exposure glass, 4 – optical fiber, 5 – RGB LEDs.

4. Models of flatbed scanners

Despite being relatively easy to use, flatbed scanners are rather complex opto-electro-mechanical devices. Regardless of the manufacturer, the interface, the size, and the specifics of scanning technology, all flatbed scanners have plane-horizontal design, while the designs of their scanning elements may vary. The most frequently used are the following models: CIS, LIDE and CCD [5–7].

A scanner using CIS (contact image sensor) technology contains no optics. The light source, consisting of three groups of LEDs that generate light in red, green and blue wavelengths, is mounted on the scanning carriage. The total white light falls on an object and reflects back returning to the scanning head with a line of photo detectors located in close proximity of the scanner glass. The length of the light-sensitive head equals the width of the scanner's glass, so the additional optics elements (mirrors, prisms, lenses) in the scanner are unnecessary.

Scanners with LIDE (LED indirect exposure) are an improved version of the CIS technology. Here the light source uses powerful tri-color RGB (Red, Green, Blue) LEDs, and the radiation is directed to the object via quartz fibers ensuring uniform exposure over the entire width of the original scanner window (Fig. 3).

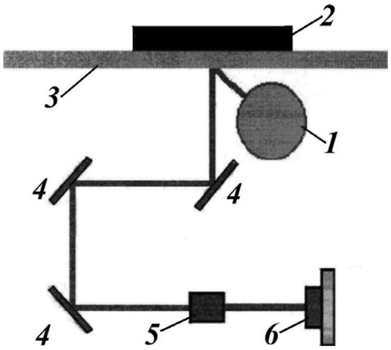

Fig. 4. Element layout in a CCD scanner: 1 – light source, 2 – object, 3 – exposure glass, 4 – mirrors, 5 – lens, 6 – CCD matrix.

Cylindrical lenses collect light scattered by the object into homogeneous bundles and focus that light onto a line of phototransistor converters array with high signal /noise value/resolution and high sensitivity in comparison with any other existing sensors (Fig. 3b).

As opposed to the CIS and LIDE technologies, an optical system of a CCD (charge coupled device) flatbed scanner consists of a lens and mirrors or prisms that project the light flux from the object being scanned onto the photodetector system (Fig. 4).

The photodetector system consists of three parallel CCD arrays with an equal number of identical light-sensitive elements, each with its red, green and blue filter, receiving information on the content of “their” colors in the light flux from the object being scanned. CCD scanners use fluorescent lamps. If transparent samples are scanned, a so-called slide adapter is used with a second lamp located in the cover of the scanner. This lamp is moving strictly parallel to the read head scanner.

5. Main characteristics of scanners

Optical resolution is the number of elements in the liner array of photodetectors divided by the maximum width of the scanned area, i.e., the width of the scanner’s glass (dpi-parameter). The maximum dpi value for CCD scanners is 9600, for LIDE scanners it is 4800. This parameter determines the number of channels through which the parallel light intensity from the object is measured, and the linear dimensions of each channel (see table).

Mechanical resolution is the number of information “reads” done by the line array of photodetectors (number of rows), divided by the length of the path traveled by the scanning carriage during the same time. This is often incorrectly referred to as the optical resolution but typically, the mechanical resolution is two times the optical one and is determined by the manufacturer.

Interpolated resolution is a number that specifies the resolution up to which the scanner calculates missing pixels (e.g., if only 3×3 pixels are received, the scanner will calculate 16×16 pixels). This option should not be used in physical research.

Color depth (the number of bits per color). The average amount of binary color information for a point of a full-color image is 24 bits per point, and 8 bits for each of the primary RGB colors, which gives about 17 million colors. The human eye cannot distinguish more subtle shades of color.

The range of optical densities. The optical density is a characteristic of the scanned object. It is calculated as the common logarithm of the ratio of the intensity of light sent to the object to the intensity of light reflected from or transmitted through the transparent object. The minimum possible value 0.0 D corresponds to perfectly white or transparent objects, the value of 4.0 D to very black or opaque objects. The optical density range of a scanner describes its ability to distinguish between adjacent shades. The maximum optical density of a given scanner is determined by the object the scanner still can distinguish from “complete darkness”. A scanner cannot distinguish any shades darker than that object. This means that the scanner can lose all the details in dark and light areas of the scanned object. This parameter is important for physics research, as a wider range of optical densities of a scanner allows obtaining more detailed information about the object being scanned.

The following parameters of a scanner’s linear photodetecting array are very important but usually are not included in the specification.

Noise level is limiting the dynamic range and the actual number of bits of data containing useful information. If a cheap noisy linear array is connected to a 36-bit ADC, the image quality neither improves nor suffers. Note that the noise level in CCD scanners may be several times higher than in LIDE scanners. In physical research, scanner noise can be measured and taken into account when analyzing the results.

The cell-to-cell sensitivity spread in the CCD array. Even if the scanner calibration is possible, it is usually based on the averaged values of several adjacent cells, which hides fine image details.

Cross interference level is the influence of bright cells on adjacent cells that also hides fine details.

The combination of colors. In single-pass CCD scanners the color of the falling light is registered by three photodetecting linear arrays that cannot be

Table 1
Optical resolution and channels of a flatbed scanner.

Optical resolution (dpi)	Linear channel size (μm)	Number of parallel channels per cm^2
600	42.3 × 42.3	5.6 × 104
1200	21.2 × 21.2	2.2 × 105
2400	10.6 × 10.6	8.9 × 105
4800	5.3 × 5.3	3.6 × 106
9600	**2.6 × 2.6**	**1.5 × 107**

absolutely identical due to technological variance and therefore may render a distorted image.

Presence of the optical system in CCD scanners may potentially lead to image distortions caused by skew between elements of the optical system leading to non-uniform reading of information along each row. It is not the case for LIDE scanners that provide higher geometric accuracy of scanning. It should be noted that because of their long-focus optical system the CCD scanners provide greater depth of field (5 mm), unlike LIDE scanners (0.5 mm). LIDE scanners usually do not include a slide module.

6. Analysis of scanned images

Modern scanners use a 3-channel RGB system for color representation. Each channel has 256 gradations. A value of 0 corresponds to the absence of scattered components, i.e. a scanned object is a perfect mirror. A value of 255 corresponds to a perfectly diffusing surface without the mirror component. The result is $256{*}{*}3 =$ 16,777,216 colors distinguishable by computer, which is very close to the sensitivity of the human eye.

The scanner breaks the image into separate points, i.e. pixels, the number and the linear dimensions of which depend on the optical resolution of the scanner (see Table 1). Each pixel has its own color “passport”, i.e. its coordinates in RGB-space. For example, the record (185, 17, 110) means that the pixel is displayed in red with an intensity of 185, green with an intensity of 17, and blue with an intensity of 110. The computer receives these pixels with their “passports” and stores the information about them in its memory.

The scanner allows to record and analyze 10^4–10^7 independent reference points in one dimension from every square centimeter of an A4 surface (see Table 1). This is where the scanner significantly differs from systems with one-dimensional signal recording (i.e. a scanning electron microscope, a scanning tunneling microscope, an atomic force microscope, etc.). Such scanning systems have better geometric resolution but are far behind the flatbed scanners in speed and in size of the analyzed area [8].

There is a number of graphics editing tools that allow to process large amounts of information. Adobe Photoshop is one of the most commonly used tools. It allows to count the number of pixels in an image and to display brightness distribution as a histogram by averaging estimates of areas.

The Origin software is more suitable for physics research as it provides the possibility of mathematical processing of the data received from the scanner. Origin supports the creation of two-dimensional and three-dimensional scientific graphics allowing for numerical analysis of data, including various statistical operations, and carries out various analytical approximations of the results. Using this program, it is possible to construct the histogram at different scales, for example, a logarithmic. This allow to evaluate a wide range of scattered light intensity, i.e. determine the size of not only the dominant scattering structures in the object under study, but also smaller and larger elements that are rare and/or hard to see against the background.

Keeping in mind the above-mentioned features of CCD and LIDE scanners, both may be used in a physics experiment depending on the experiment objectives. In order not to distort the resulting images, the internal scanner settings should not be used and images should not be saved in JPG format as much of the valuable information is lost. Following formats could be used: TIFF, BMP, PND or RAW formats may be used [9].

One general and inherent shortcoming of all scanner models is that each scanner requires its own individual calibration, since even two scanners of the same model from the same manufacturer may significantly vary in their characteristics. Most likely this is a consequence of manual tuning for each scanner in the manufacturing proses. This does not negatively affect the quality of copying the printed materials but significantly alter the results of physical experiments.

7. Examples of method implementation

To illustrate the broad possibilities of using flatbed scanners for physical studies we are providing here some practical examples.

Fig. 5 is a bar graph of the intensity distribution of light scattered from a sapphire plate in a linear and a logarithmic scale. The logarithmic scale allows to see the inhomogeneities in plate polishing which are not visible on the linear histogram. The main peak of the histogram corresponds to the dominant plate relief; the half-width of the maximum variation reflects the

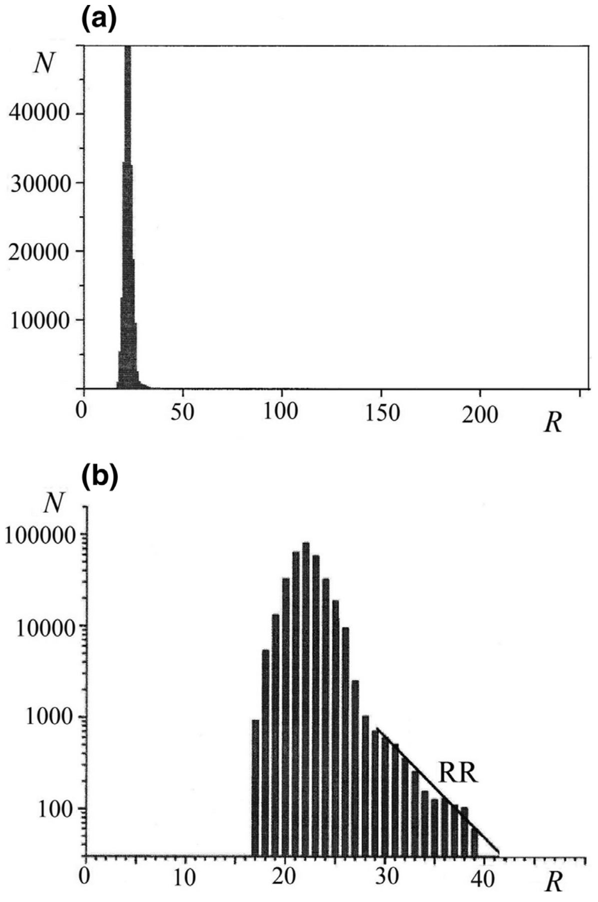

Fig. 5. Intensity distribution of light scattered from a sapphire plate (a bar graph in a linear (a) and a logarithmic (b) scale): RR (rare, roughness) – rare, more rough irregularities.

relative roughness, and the almost exponential decline to the right of the RR maximum corresponds to the rough plate surface topography, which indicates that the plate has been under-polished on the previous stage of its processing.

Fig. 6 shows the surface topography of the optical window of calcium fluoride CaF_2, produced by the scanner before and after the finishing polish. Interference fringes (Newton's rings) reveal uneven terrain. After the finishing polish the plate shows Newton rings equally spaced, which indicates there are no peaks and valleys, and a small curvature of the rings indicates a small taper surface.

Fig. 7 demonstrates the capabilities of the scanner in determining the polytype of silicon carbide crystals obtained by the Lely technology. Sample I from the set of cubic 3C-SiC crystals turned out to be a hexagonal 6H-SiC polytype. The intensity of light scattering from samples of silicon carbide in the red (R_r) and blue (R_b) wavelengths are plotted along the axes of the graph.

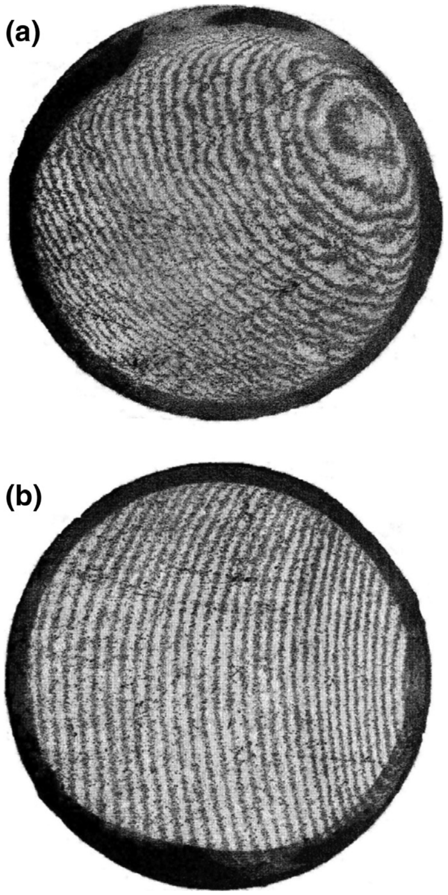

Fig. 6. CaF_2 optical window reliefs before (a) and after (b) the finishing polish.

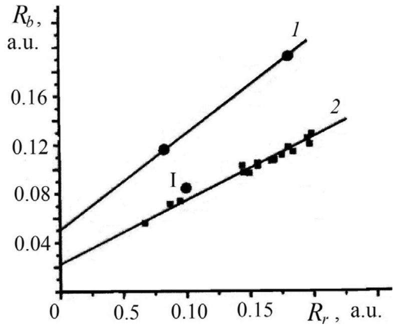

Fig. 7. Determining the silicon carbide crystals polytype: 1 – cubic 3C-SiC, 2 – hexagonal 6H-SiC. Sample I, registered as cubic, turned out to be hexagonal.

Fig. 8 shows the calibration dependences for determining the roughness of the quartz and glass plates from the scanned data. Quantitative calibration by roughness value is made through profilometer measurements. The points in the graphs correspond to the experimental data

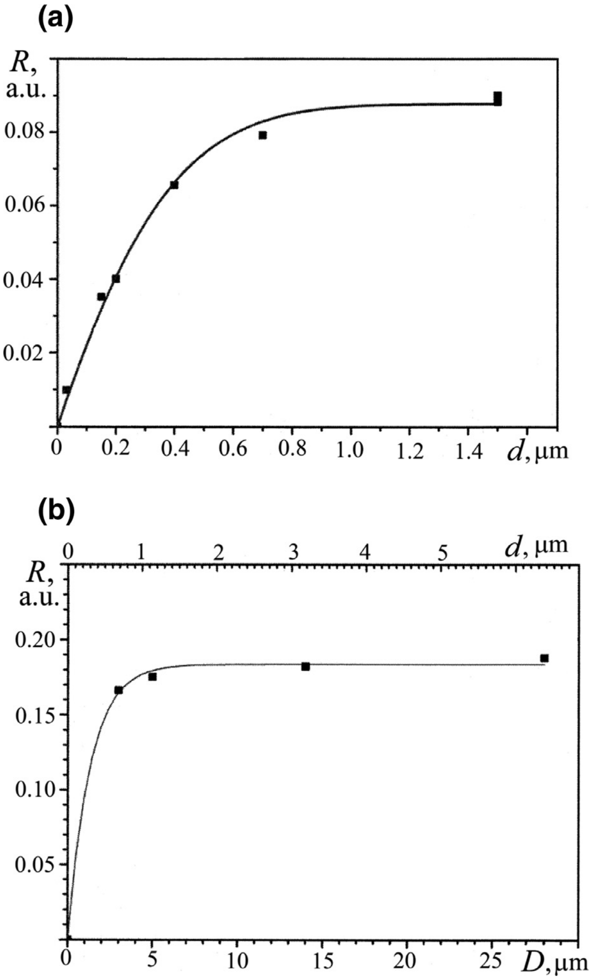

Fig. 8. Calibration dependences for determining the roughness of the quartz (a) and glass (b) plates: symbols – the experiment, solid lines – the approximation, *x* – roughness, *d* – grain size for the abrasive used for polishing.

obtained using a scanner, the solid curves to the theoretical approximation.

A detailed description of the techniques using a flatbed scanner to obtain the results shown in Figs. 5–8 is planned for future papers.

8. Conclusion

We developed a relatively inexpensive method of nondestructive surface and bulk properties testing of products and electronic materials; the method is based on using a flatbed scanner for measuring the optical inhomogeneity of objects by the parameters of radiation scattered by these objects.

Control objects can be solid, liquid and bulk semiconductor, dielectric, and metal objects. Control may be performed simultaneously for a series of samples placed within the operating window of the scanner (290 × 210 mm), irrespective of their number, size and shape.

The method is intended for use primarily in production: for 100% factory control, and for selective speed-control in industrial laboratories, but is also of interest for research purposes.

The versatility of the method is determined by the fact that it combines a sufficiently high sensitivity and resolution, speed measurement, compact measuring equipment, ease of maintenance, lack of strict requirements for the placement and installation and relatively low price.

The principal difference of this method from the methods using highly specialized equipment is that with the low cost and easy processing it is possible to measure a wide range of physical parameters of materials with a sufficiently high accuracy by processing a large volume of information obtained from the controlled object.

Currently, the following techniques have been developed in laboratory conditions:

1. Measuring the physical parameters of materials (from nearly transparent to almost completely black in the visible region of the spectrum);
2. Measuring the degree of roughness (from 2 nm and rougher) for polished and buffed flat surfaces, their processing uniformity over the area of the object portions with lateral resolution of 3–10 μm; quantifying the degree of surface under-polishing at each processing stage, i.e. identify rough terrain, including scratches, against the more shallow one;
3. Dividing the light scattered from transparent objects into components (the scattering from the bulk, from the front and back surfaces) in order to separately characterize the surface and bulk properties of the object;
4. Defining the number, position and size of defects, their shape and dimensions within the optical resolution of the scanner.

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