High-frequency imaging for flaw detection of microelectronics elements with high resolution

S N Zhakupov¹, A V Badin²

¹Student, National Research Tomsk State University, Tomsk, Russia
²Associate professor, National Research Tomsk State University, Tomsk, Russia
E-mail: Zhak.sn@yandex.ru

Abstract. This paper presents various diagnostic methods for microelectronic devices, in particular integrated circuits (IC). Features with the use of electron microscopes, scanning infrared microscopes, as well as X-ray flaw detection are considered. In particular, it is proposed to use a method based on electromagnetic radiation from the terahertz frequency range as an alternative to X-ray computed tomography (PXCT). For flaw detection of integrated circuits, it is planned to create a database of materials by preliminary spectral analysis of the materials used to create them. The possibility of analysis by creating two-dimensional patterns of the distribution of the intensity of electromagnetic radiation transmitted through the sample is also considered.

1. Introduction

The continuous development of science and technology in the modern world leads to the widespread introduction of electrical products in all spheres of human life. At the same time, due to the desire to integrate all kinds of functions of various devices into one, the components of these devices acquire an increasingly complex structure, while their sizes do not increase, but often decrease. A clear confirmation of this process is the continuous increase in the number of transistors placed on the integrated circuit chip, which is reflected in the so-called “law” of Moore. Modern integrated circuits (ICs) have a high density of structurally inseparable and electrically connected elements, components and crystals, which are considered indivisible by the requirements for testing, acceptance, delivery and operation. These aspects cause problems associated not only with the complication of the process of production of microelectronics elements, but also with the quality control of products (performance analysis, identification of defects). Overcoming the problems associated with the control of the technological process leads to a low percentage of rejects, lower time costs for each unit produced, as well as a decrease in the total cost of production.

2. Actual methods for monitoring integrated circuits

At present, several “classical” control methods can be distinguished - this is operational control, visual control and control of electrical parameters [1–4]. Considering integrated circuits as an object of study, it is worthwhile to understand that they contain a large number of structural elements - a lot of conductors and their intersections, interlayer junctions, directly the components themselves (package diodes, transistors, capacitors, resistors, small-sized inductors and transformers) and their conclusions. All this virtually eliminates the full control of all elements by electrical parameters due to the high complexity. In this regard, optical control methods are actively involved [5, 6]. For example, microscopes with high magnification are used to assess the state of the surface, determine excess or insufficient etching, change...
the thickness of the oxide layer, the correct transition and porosity of the oxide layer. Scanning electron microscopes are also used, which make it possible to obtain a topographic relief of the integrated microsphere, to identify track defects, dust particles, punctures in the oxide layer and scratches on a thin metallization layer. Using electron microscopes, it is possible to obtain a contrasting image of energized IC components (for example, a resistor has a gradient transition from dark at one end to light at the other), taking images of healthy components as a reference, it becomes possible to identify defective elements by direct comparison. To assess thermal profiles (heat and power dissipation) with the identification of superheated areas, infrared scanning microscopes are used. Thermographic systems based on the use of thermosensitive inks can be considered an analogue of these microscopes - thermosensitive inks applied to the surface of an integrated microcircuit, placed under a load, are painted in different colors, which allows observing the IC under a microscope to record the temperature change with an accuracy of 0.5°C. Also used metallographic analysis, consisting in the examination of transverse or oblique sections, which allows to identify their internal structure and detect not wetted when soldering, penetration, microcracks, shells, pores, intermetallic inclusions, traces of solder diffusion along grain boundaries.

Recently, X-ray flaw detection has been actively used. In simpler versions, it allows using a diverging beam to detect internal defects and provides sufficient information about the reliability of the connections [7–9]. However, there are works [10] describing the process of obtaining a full three-dimensional model of the structure of the IC, this method is called x-ray computed tomography (ptychographic X-ray computed tomography - PXCT). This method is based on the selection of structural objects of the IC due to the difference in bulk densities, i.e. knowing in advance what this or that microcircuit consists of (knowing the electrodynamic properties of the materials used), it is possible to identify the components of the IC. The process of compiling a three-dimensional picture is as follows - the first step is to collect data on the properties of the materials used in the sample, the second step is direct x-ray computed tomography (the object must be in free space, and also have rotation), followed by calibration of the data and identification microelectronic components (by comparing the obtained values with a reference database), then there is a construction of a two-dimensional model of the investigated area And Since, ultimately results obtained by composing the three-dimensional model is created.

3. Terahertz non-destructive control method

In this work, it is proposed to use the STD-21 terahertz spectrometer as a functional setup. Unpackaged backward-wave lamps are used as a radiation source, which provide overlapping of the frequency range from 60 GHz to 1.5 THz. The main advantages of this source is the ability to select the desired frequency and stability of generation. Due to the fact that many materials have their own characteristic spectra in this frequency range, it seems possible to identify the components of the integrated circuit by comparing the obtained scan results with a pre-prepared database. It also seems possible to obtain the required number of different two-dimensional models of the investigated integrated circuit for subsequent analysis, calibration and compiling them into a full-fledged three-dimensional IC model.

Already at this stage, it is worth noting that the energy of the emitted X-ray radiation is orders of magnitude greater than the maximum achievable energy of the terahertz frequency range when using backward-wave lamps in the range from 60 GHz to 1.5 THz. This aspect can be considered from two sides, on the one hand this means that electromagnetic radiation of the terahertz frequency range does much less harm to human health than x-ray radiation, and on the other hand, lower radiation power leads to less penetrating ability.

Partially, the penetration problem can be solved with additional focusing elements. In particular, using the cubic focusing element Figures 1, 2.
For the most successful variant of the interaction of an electromagnetic wave with a focusing element, it is necessary to choose the material from which the cube is made with a refractive index $n$ in the range $1.4 - 1.6$. The geometric dimensions of the edges of the cube should correspond to the wavelength of the generated electromagnetic radiation, and also the element itself should be as symmetrical as possible.

To practically demonstrate the operation of the focusing element, a sample was prepared consisting of a sheet of paper with metal strips deposited on its surface (Figure 3a). The generated frequency was chosen equal to 42 GHz, which corresponds to a wavelength $\lambda \approx 7$ mm, based on the value of the wavelength, the width of the strips and the distance between them was chosen so as to minimize unwanted interference, and approximately determine the diffraction limit of the system. The cube was made using the additive technology of ABS plastic with a refractive index of $n = 1.62$ and an edge length of 7 mm.
Figure 3. a) Image of a test sample with metal stripes; b) The dependence of the relative power at the detector on the position of the metal strips at a frequency of 42 GHz.

Figure 3b shows the dependence of the power supplied to the detector on the position of the sample relative to the estimated center of the electromagnetic beam focused by the system. The dependence shown by the red line is removed without an additional focusing element. It is seen that we can determine only the widest band, the width of which exceeds the wavelength, followed by a series of imaginary maxima and minima. The black line shows the dependence of the intensity on the coordinate taken using the focusing element, it is worth noting that in addition to the fact that the intensity minima coincide with the centers of the metal strips, we can detect lines whose width is more than three times less than the wavelength.

Figure 4. The result of visualization of the intensity distribution matrix of transmitted electromagnetic radiation in a two-dimensional plane with (a) and without using a focusing element (b). Shades of gray characterize the signal level from the detector in absolute units.

Figure 4 presents a two-dimensional picture of the distribution of the intensity of electromagnetic radiation transmitted through the sample [11]. Since the terahertz spectrometer used is designed for the point-to-point taking of electrodynamic characteristics, a displacement module in two-dimensional space was used Figure 5b [12]. Both of the presented modules allow you to move the objects of study at a given step at a given speed, this allows you to build two-dimensional pictures when taking the energy characteristics of electromagnetic radiation and phase shift introduced by the sample.
Figure 5. Positioning module for objects with maximum dimensions: a) 400×400 mm; b) 40×40 mm.

As a detector, an acousto-optical converter (Goley cell) is used, which is characterized by high sensitivity and noise immunity.

4. Results
Combining the possibility of the identification of materials through spectral analysis, the classical "clearance" of the sample with the possibility of increasing the resolution, we obtain a method of non-destructive testing, which has its own advantages. The main one is the safety of the type of radiation used relative to x-ray radiation. This method allows you to diagnose the internal composition of the sample, detect hidden damage, and also create a three-dimensional concept model.

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