Continuous terahertz wave imaging of microelectronics objects

A I Berdyugin and A V Badin
Radio electronics Department, Faculty of Radiophysics, National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russia
E-mail: aleksanderberdyugin@gmail.com

Abstract. The results of using a terahertz imaging system for microelectronic flaw detection are presented. The distribution of the transmitted radiation through the plastic leaded chip carrier microchip at frequencies of 206 and 806 GHz is obtained. The possibility of using quasi-optical systems with a continuous terahertz radiation source for microelectronic flaw detection has been evaluated.

1. Introduction
Today, technologies using electromagnetic radiation in the terahertz frequency range are among the most promising. The prospects for widespread application of the terahertz frequency range are due to the following factors: the terahertz radiation quantum is not ionizing [1, 2]; the penetrating capacity of electromagnetic radiation of the terahertz range through fine dielectric mediums [3], owing to a sharp decrease in the level of Rayleigh scattering [4]; the high throughput of terahertz radiation, compared with the operating frequency of the existing element base. Because the terahertz spectrum contains resonances of important organic molecules [5] and many crystal lattices [6], new spectroscopy methods are being developed [7] for biological and semiconductor materials.

The relevance of astrophysical research in the terahertz frequency range is due to the fact that approximately half of the total glow and 98% of the emitted photons since the Big Bang are in the submillimeter and far infrared ranges [8]. Over the last 30 years, because of the interest in research in the terahertz portion of the electromagnetic spectrum, the number of research papers related to terahertz spectroscopy has increased significantly [9]. This is primarily caused by the progress of methods for generating terahertz radiation (high-power femtosecond lasers [10], sources based on a back-wave lamp [11], etc.), and also owing to the fact that terahertz radiation is non-ionizing [1, 2] (the photon energy is 0.1-0.001 eV). The terahertz range of radio waves is still poorly developed technically, the element base of this spectrum (generators, detectors, data transmission lines, antennas, converters) is mostly still being developed [9].

One of the most popular applications of terahertz radiation is the detection of optical hidden images [12], imaging and spectroscopy of art objects [13, 14], as well as objects of cultural and historical value [15]. To solve these problems, it is necessary to develop new functional composite materials, the most promising basis for which are carbon nanotubes [16], graphene [17, 18], ferrites [19], carbon onion structure [20], nanofibers [21] and ferroelectric [22].

The development of higher-frequency elements requires additive technology to increase spatial resolution. In this case, one of the approaches to solving this problem is a combination of numerical
modeling in CAD and experimental verification using terahertz visualization systems [25] and subsequent correction of the mathematical model.

It is known that to increase the resolution of scanning systems, the frequency of electromagnetic radiation interacting with the sample increases. But this method has one drawback: reducing the penetrating ability of the radiation used due to signal attenuation. The active development of subwavelength quasi-optics contributes to improving the efficiency of THz scanners [26]. Such systems allow us to provide high spatial resolution in the lower part of the THz range, where the most effective interaction of radiation with the material under investigation occurs. Today, much attention is paid to subwavelength defectoscopy of integrated circuits [27]. Where, due to the use of a small dielectric particle forming a photon jet [28], it is possible to increase the spatial resolution of quasi-optical material diagnostics systems by 1.6 times [29]. Small wavelengths in the submillimeter range make it possible to determine inhomogeneities of controlled objects with high accuracy and locally distinguish their chemical structure [30].

Despite the fact that terahertz time-domain spectroscopy (TDS) [31] methods are widely used, the application of continuous terahertz radiation in the diagnosis of defects in modern electronic components of microchips is of interest. The disadvantages of TDS include: the complexity of the technique used; the high price, in comparison with systems with continuous radiation, the trade-off between high resolution and accurate chemical composition detection. Using a source of continuous terahertz radiation, tunable in frequency, targeting certain points of the component of the microchip, it is possible to determine its chemical structure, thereby evaluating its quality by comparing the characteristics with the standard base.

Detection of defects at various stages of manufacturing allows automatizing the conveyor, reducing the cost of manufactured components and increasing the company's profit. By identifying the cause of a counterfeit product defect, possible increase manufacturing efficiency. In comparison with other methods of non-contact microelectronics monitoring (x-ray, ultrasonic, optical), terahertz flaw detection has several advantages. Namely, the ability to look inside the object under study in a non-destructive way; ease of processing the results, which reduces the measurement error; safety for biological objects; ease of building visualization systems, and relative cheapness of components compared to more accurate X-rays. Such systems are able to assess the integrity of the silicon shell, gold conductors from the crystal to the pins, as well as the pins of the chip itself.

2. Experiment
Microelectronics objects was monitored using a developed terahertz imaging system (system for recording two-dimensional distribution of radiation intensity) [32]. The scanning system has a deep penetrating capacity, is easily integrated into the quasi-optical path of the measuring spectrometer, and also allows to determine the properties of the substance that makes up the object by analyzing the obtained frequency characteristics. In addition, the nondestructive diagnostics system is fully automated and the operator's participation is necessary only at the initial adjustment stage.

2.1. Methods and materials
The object (Figure 1) of non-destructive terahertz imaging was a typical plastic leaded chip carrier (PLCC). The main characteristics of the object under research: the geometric size of the chip – 11.58 x 11.58 mm, the number of pins – 28 pieces, upper lead width: 740 µm, step between pins: 1.27 mm; lower lead width: 0.51; lead thickness: 270 µm; molded package thickness: 3.87 mm; 7 pins per side.
Figure 1. Sample of investigated PLCC microchip (left) and two axis linear stage (right).

In the two-dimensional orientation mechanism of the image system the sample was placed and then fixed by hot melt on sheet of paper with thickness 100 µm. The mechanism integrated into the quasi-optical path of the STD-21 terahertz spectrometer moved the sample in a two-dimensional area sequentially (step by step) relative to the electromagnetic beam of the terahertz frequency range. The system was mechanized using stepper motors controlled by the digital I/O module L-card E-154. A schematic diagram of the terahertz imaging system is shown in Figure 2.

Figure 2. Scheme of the quasi-optical path of the system for noncontact control of microelectronics objects.

As tunable sources of the continuous monochromatic radiation a backward wave oscillator (BWO) was used. Using a Golay cell and a 12-bit analog-to-digital converter of the E-154 module the transmitted radiation was detected. The I/O module was controlled by software written in the LabVIEW (G) language. The non-destructive testing instrument of the chip was monochromatic electromagnetic radiation with an operating wavelength of λ=371 µm (806 GHz) and λ=1.46 mm (206 GHz).
2.2. Results
The values of transmission digitized by the E-154 module from an optoacoustic transducer (Golay cell) at set points on the sample plane together create an image of the distribution of the terahertz radiation intensity transmission through the sample with a frequency of 806 GHz (Figure 3) and 206 GHz (Figure 4).

Figure 3. Intensity distribution of THz radiation (λ=371 µm) transmitted through the chip.

Figure 4. Intensity distribution of THz radiation (λ=1.46 mm) transmitted through the chip.

Analyzing the image obtained using the terahertz imaging system, we can say that there are voids in the sample under study and their boundaries are distinguishable. The voids are located closer to the center, symmetrically around the crystal at equal distances from it. The nature of the chip voids is caused by a construction characteristic of the chip manufacturer in this type of case (a small number of pins – 28 pieces) and does not indicate the presence of defects. Due to the change in spatial resolution with increasing frequency, the image detail increases. J-formed Cu leadframe with diameter 1.27 mm becomes visible at 806 GHz (Figure 3), in comparer with case of 206 GHz (Figure 4).

3. Conclusion
As a result of this work, the authors obtained the information about the internal structure of the integrated circuit in the PLCC case. Thus, the possibility of using terahertz imaging of microelectronics objects in order to detect hidden defects is confirmed. The prospects of conducting research in the terahertz wavelength range are proved.

This technique is inferior in diagnostic precision to systems based on x-ray radiation of the wavelength range. But due to the non-ionizing capacity of terahertz radiation and its prospects due to the presence of many resonances of various molecules in the spectrum, x-ray radiation is inferior to it. Thus, for example, using a previously obtained image of the distribution of the radiation intensity that passed through the sample, it is possible to determine the chemical structure of local voids inside the sample using spectral analysis. In turn, increasing the image resolution or scanning at a lower frequency, where the most effective interaction of radiation with the material under study occurs, while maintaining the spatial resolution, is possible due to the use of a small dielectric particle [29].

Acknowledgments
The reported study was funded by RFBR according to the research project No. 20-32-90125.

References
[1] Son J H, Oh S J and Cheon H 2019 Potential clinical applications of terahertz radiation J. Appl. Phys. 125 190901
[2] Mattsson M O and Simkó M 2019 Emerging medical applications based on non-ionizing electromagnetic fields from 0 Hz to 10 THz Med Devices (Auckl) 12 347

[3] Markl D, Wang P, Ridgway C, Karttunen A P, Chakraborty M, Bawuah P, Gane P, Ketolainen J, Peiponen K and Zeitler J A 2017 J. Pharm. Sci. 106 1586-95

[4] Han P Y, Cho G C and Zhang X C 2000 Time-domain transillumination of biological tissues with terahertz pulses Opt. Lett. 25 242-4

[5] Gong A, Qiu Y, Chen X, Zhao Z, Xia L and Shao Y 2020 Bio-medical applications of terahertz technology Appl. Spectrosc. Rev. 3 418-38

[6] Tan T C, Plum E and Singh R 2019 Surface lattice resonances in THz metamaterials Photonics 6 75

[7] Dexheimer S L 2017 Terahertz spectroscopy: principles and applications CRC press.

[8] Leisawitz D 2000 Scientific motivation and technology requirements for the SPIRIT and SPECS far-infrared/submillimeter space interferometers Proc. SPIE 4013 36-46

[9] Mittleman D M 2017 Perspective: Terahertz science and technology J. Appl. Phys. 122 230901

[10] Kitaeva G K 2008 Terahertz generation by means of optical lasers Laser Phys. Lett. 5 559-76

[11] Cai J, Wu X and Feng J 2014 Traveling-wave tube harmonic amplifier in terahertz and experimental demonstration IEEE Trans. Electron Devices 62 648-51

[12] Cooper K B, Dengler R J, Llombart N, Thomas B, Chattopadhyay G and Siegel P H 2011 THz imaging radar for standoff personnel screening IEEE Trans. Terahertz Sci. Technol. 1 169-82

[13] Fukunaga K, Ikari T and Iwai K 2016 THz pulsed time-domain imaging of an oil canvas painting: a case study of a painting by Pablo Picasso Appl. Phys. A 122 106

[14] Guillet J P, Wang K, Roux M, Fauquet F, Harraq F and Mounaix P 2016 Frequency modulated continuous wave terahertz imaging for art restoration J. Infrared Millim. Terahertz Waves 1

[15] Cosentino A 2016 Terahertz and cultural heritage science: examination of art and archaeology Technologies 4 6

[16] Hartmann R R, Kono J and Portnoi M E 2014 Terahertz science and technology of carbon nanomaterials Nanotechnology 25 322001

[17] Tasolamprou A C, Koulouklidis A D, Daskalaki C, Mavidis C P, Kenanakis G, Deligeorgis G, Viskadourakis Z, Kuzhir P, Tzortzakis S, Kafesaki M, Economou E N and Soukoulis C M 2019 ACS Photonics 6 720-7

[18] Batrakov K, Kuzhir P, Maksimenko S, Volynets N, Voronovich S, Paudubskaya A, Valusis G, Kaplas T, Svirko Yu and Lambin P 2016 Enhanced microwave-to-terahertz absorption in graphene Appl. Phys. Lett. 108 123101

[19] Badin A V, Dorozhkin K V, Kuleshov G E, Zhuravlev V A, Suslyaev V I, Dunaevskii G E and Bilinski K V 2018 Ferromagnetic resonance in hexagonal ferrite BaFe 12 O 19 at the EHF frequency range J. Infrared Millim. Terahertz Waves 1-2

[20] Okotrub A V, Bulusheva L G, Larionova I S, Kuznetsov V L and Molodtsov S L 2007 Diam. Relat. Mater 16 2090-2

[21] Das A, Megaridis C M, Liu L, Wang T and Biswas A 2011 Appl. Phys. Lett. 98 174101

[22] Wu Y, Isakow D and Grant P S 2017 Fabrication of composite filaments with high dielectric permittivity for fused deposition 3D printing Materials 10 1218

[23] Li S, Dai Z, Wang Z, Qi P, Su Q, Gao X, Gong C and Liu W 2019 A 0.1 THz low-loss 3D printed hollow waveguide Optik 176 611-6

[24] Adams J J, Duoss E B, Malkowski T F, Motala M J, Ahn B Y, Nuzzo R G, Bernhard J T and Lewis A J 2011 Advanced Materials 23 1335-40

[25] Perraud J B, Obaton A F, Bou-Sleiman J, Recur B, Balacey H, Harraq F, Guillet J P and Mounaix P 2016 Applied Optics 55 3462-7

[26] Zagreopoulos D C, Algorri J F, Ferraro A, García-Cámara B, Sánchez-Pena J M and Beccherelli R 2019 Toroidal metasurface resonances in microwave waveguides Scientific Reports 9 1-11

[27] Ahi K, Shahbazmohamadi S, Asadizanjani N 2018 Quality control and authentication of packaged integrated circuits using enhanced-spatial-resolution terahertz time-domain spectroscopy and...
imaging *Opt. Lasers Eng.* **104** 274-84

[28] Minin I V and Minin O V 2014 Experimental verification 3D subwavelength resolution beyond the diffraction limit with zone plate in millimeter wave *Microw. Opt. Technol. Lett* **56** 2436-9

[29] Zhakupov S, Badin A and Berdyugin A 2019 The practical application of subwavelength focusing elements in the EHF imaging system *ITM Web of Conferences* **30** 12008

[30] Dhillon S S, Vitiello M S, Linfield E H, Davies A G, Hoffmann M C, Booske J and Castro-Camus E 2017 The 2017 terahertz science and technology roadmap *J. Phys. D. Appl. Phys.* **50** 043001

[31] Ajito K, Nakamura M, Tajima T and Ueno Y 2017 Terahertz Spectroscopy Methods and Instrumentation (Elsevier)

[32] Badin A V, Dorozhkin K V, Suslyaev V I, Berdyugin A I and Vigovskiy V Y 2017 *23rd International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics* **10466** 1046625