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TERAHERTZ EMITTERS BASED ON NEGATIVE-U MATERIALS FOR MEDICAL APPLICATIONS

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Abstract. The characteristics of terahertz (THz) irradiation generated by a silicon nanosandwich structure under the conditions of a stabilized drain-source current are demonstrated. The frequency of irradiation arising from the quantum Faraday effect is determined by the parameters of microcavities embedded in the edge channels of a silicon nanosandwich structure confined by the negative-U centers. The obtained characteristics of a compact THz irradiation source determine the basis for highly effective medical applications.
Keywords: silicon nanosandwich structure, negative-U centers, terahertz irradiation, IR Fourier spectrometer

1. Introduction

In recent years, studies of materials and nanostructures based on them, which make it possible to detect macroscopic quantum effects at high temperatures up to the room temperature have been of great interest [1-6]. One of the main conditions for revealing these effects is the effective neutralization of electron – electron interaction in the edge channels of nanostructures. For this reason, the high-temperature Shubnikov-de Haas, de Haas-van Alphen oscillations, the Hall resistance quantum staircase, and the longitudinal conductance quantum staircase were observed in graphene, in several related topological insulators and superconductors [1,2], as well as in silicon, 6H-SiC and CdF_2 nanostructures, in which the edge channels are confined by the chains of the negative-U centers [3-6]. It should be noted that the neutralization of the electron – electron interaction in the edge channels is also predicted when they are confined by the chains of d- or f-elements [7,8]. But, the coatings consisting of the negative-U centers appear to contribute more effectively to the observation of macroscopic quantum phenomena at high temperatures [3-6]. Moreover, among the observed macroscopic quantum phenomena, the Faraday quantum effect takes the important part, which, as it was fined, gives rise to the capture of the single magnetic flux quanta to the edge channels containing single carriers, thereby emitting irradiation in the THz- and GHz frequency range depending on edge channels length [3,5]. It was shown that it is possible to control the frequency and amplitude characteristics not only by varying the dimensional parameters of the edge channels but also by incorporating various microcavity systems into them [4-6]. Thus, various versions of compact terahertz irradiation sources were developed, which are widely used in practical medicine [9].

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It should be noted that terahertz irradiation is becoming more widespread in world therapeutic practice [10]. Moreover, the far-IR and THz range include irradiation with a wavelength of 10 to 1000 μm, respectively, with a frequency of 300 GHz to 30 THz, therefore a specific frequency or wavelength is usually indicated for its unambiguous characteristic. Moreover, the combination of GHz, THz, and IR radiation is of the greatest interest for the direct therapeutic effect on biological tissues, because the IR irradiation can stimulate the most important biochemical reactions in the human body, while the THz component of the irradiation provides a resonant increase of this effect due to the bonds "shaking" in protein molecules [9], and GHz modulation affects the longitudinal vibrations of the DNA-oligonucleotides [4,6].

This combination of modulating frequencies can be implemented in the same way as the principle of synchronous detection widely used in radio engineering in the range of radio waves, in which the short-wave radiation (high frequency) is modulated by the long-wave radiation (low frequency). It is clear that in the case of the optical wavelength range, the shorter THz irradiation should be modulated by the longer wavelength GHz irradiation. The advantages of such a symbiosis are obvious, but until recently, the technical implementation of sources with similar characteristics was practically impossible. However, the developed compact sources of the THz irradiation from the edge channels of silicon nanostructures made it possible to create a broadband THz emitter operating in the wavelength range of 1 – 700 μm with THz modulation (40 GHz – 3.5 THz) in the entire irradiation spectrum [9]. As noted above, this emitter is used in various fields of practical medicine with a high therapeutic effect, which is demonstrated in this article by the example of the highly effective treatment results of patients with pulmonary pathologies.

2. Silicon source of THz irradiation

A silicon nanostructure is a silicon nanosandwich (SNS) that represents an ultra-narrow p-type silicon quantum well (p-Si-QW) confined by δ-barriers heavily doped with boron (5×10^{21} cm^{-3}) on the n-Si (100) surface (Fig. 1a, b) [3,5]. SNS are formed within the framework of the Hall geometry in the process of preliminary oxidation and subsequent short-time diffusion of boron from the gas phase [3,5]. It was shown that boron atoms in the δ-barriers align crystallographically oriented sequences of the negative-U trigonal dipole centers ($B^+ - B^-$), which are formed as a result of the negative-U reaction: $2B_o \rightarrow B^+ + B^-$ [3,5]. It was found that the presence of the negative-U dipole boron centers quenches the electron-electron interaction, thereby allowing the macroscopic quantum phenomena at high temperatures, up to the room temperature [3,5]. Moreover, the most effective quenching of the electron-electron interaction is achieved in the edge channels of the quantum well confined by the negative-U dipole boron centers. It should be noted that the magnitude of the negative correlation energy is determined by the degree of the interplay of the electron-vibrational interaction and the charge correlations and is revealed by the appearance of a local phonon mode [3,5]. Detailed studies of the conductivity angular dependences made it possible to determine the value of the negative correlation energy for the dipole boron centers, 0.044 eV, which demonstrates the possibility of observing macroscopic quantum phenomena at high temperatures.

As a result of the effective neutralization of the electron-electron interaction, the holes located inside the edge channels form the chains of the quantum harmonic oscillators generating terahertz (THz) and gigahertz (GHz) irradiation due to the Faraday quantum effect under conditions of stabilized drain-source current flowing along edge channels of the SNS, which induces the appearance of a magnetic field. In turn, the emerging magnetic flux quanta, $h/2e$, (magnetic field lines) are captured on segments of the edge channels (pixels) containing single holes because of the neutralization of the electron-electron interaction and, as a result of the Faraday effect, induce a current in the pixels, which leads to the THz and GHz generation: $I_{ind}\ \Delta\Phi = E(h\nu)$, where: $\Delta\Phi_{=}\ \Phi_{0=}\ h/2e$. Depending on the value of the stabilized drain-source current, two THz generation mechanisms are possible [4,6,9]. At low currents ($<9\ 10^{-7}$A), the above mechanism dominates, arising from the generation of current in pixels during the capture of single magnetic flux quanta. For currents much higher than the above value, the generation of the THz irradiation occurs similarly to a frame bounded by two back-to-back Josephson junctions. In this case, the generation frequency is determined from the known relation: $h\nu=2e\ I_{ind}R$, where $R\ =h/2e^2$ - the quantum of resistance corresponds to a pixel with a single hole. Taking into account the density value of two-dimensional holes in the used SNS structures, $3\ 10^{13}\ m^{-2}$, the sizes of pixels with a single hole correspond to 16.6 μm x 2 nm, which, in turn, leads to the predominant generation of the THz irradiation with a frequency of 2.8 THz.

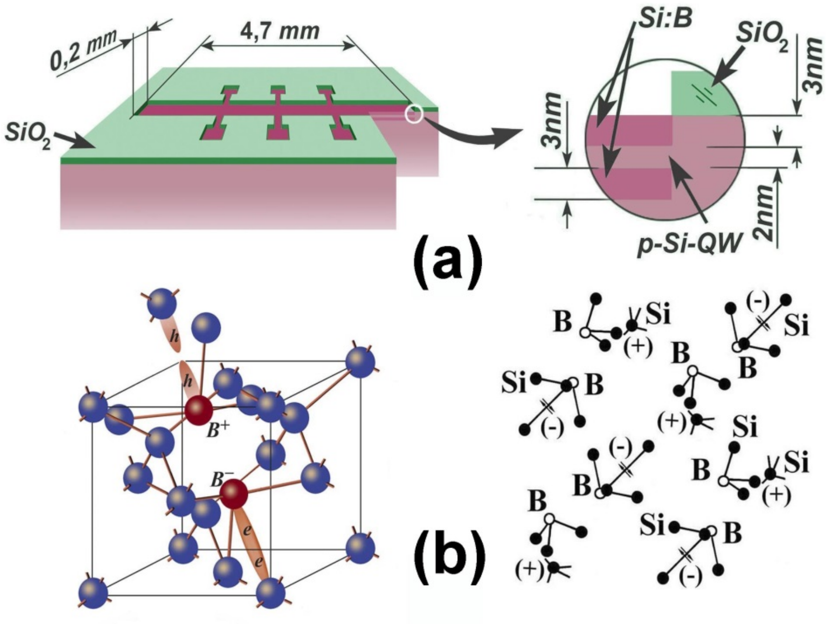

Fig. 1. (a) Design of SNS with typical dimensions. (b) The dipole trigonal center of boron (B^+ - B^-) with the negative-U energy and the chains of boron dipole centers in the δ - barriers confining p-Si-QW

Accordingly, in the presence of microcavities with sizes that are consistent with the sizes of the pixels or their groups that are built into the edge channels, the THz irradiation power can increase significantly. Also, by varying the parameters of the microresonators embedded in the SNS edge channels in the presence of negative-U centers, it is possible to select the THz generation frequency [3-6].

Thus, the characteristics of the built-in microcavities determine the shape of the THz emission spectra corresponding to one or another frequency range of the electromagnetic spectrum. For example, as noted above, to obtain effective radiation with the frequency of 2.8 THz, which is extremely important for biology and practical medicine [11-13], it is necessary, according to the sizes of the pixels containing single holes, to insert microcavities with a size of 16.6 μm into the edge channels, the presence of which is reflected in the electroluminescence spectra as the Rabi splitting (Fig. 2a) [4].

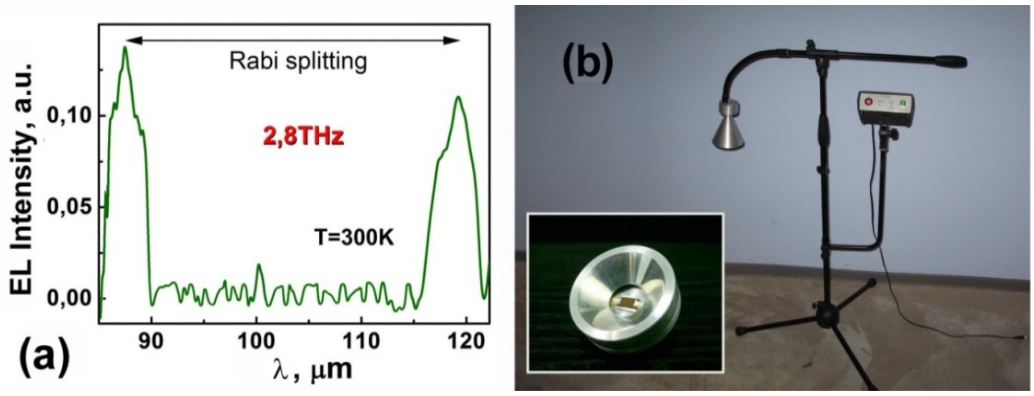

Fig. 2. (a) Electroluminescence spectrum of SNS with embedded microcavities, demonstrating the contribution of a microcavity with a characteristic size of 16.6 μm as the Rabi splitting under the conditions of the THz generation by a quantum harmonic oscillator at the frequency of 2.8 THz, which is extremely important for biology and practical medicine. I_{ds} = 30 mA. (b) the "IR-Dipole" therapeutic equipment for IR and THz therapy; the IR-THz emitter used in the apparatus is shown in the insert

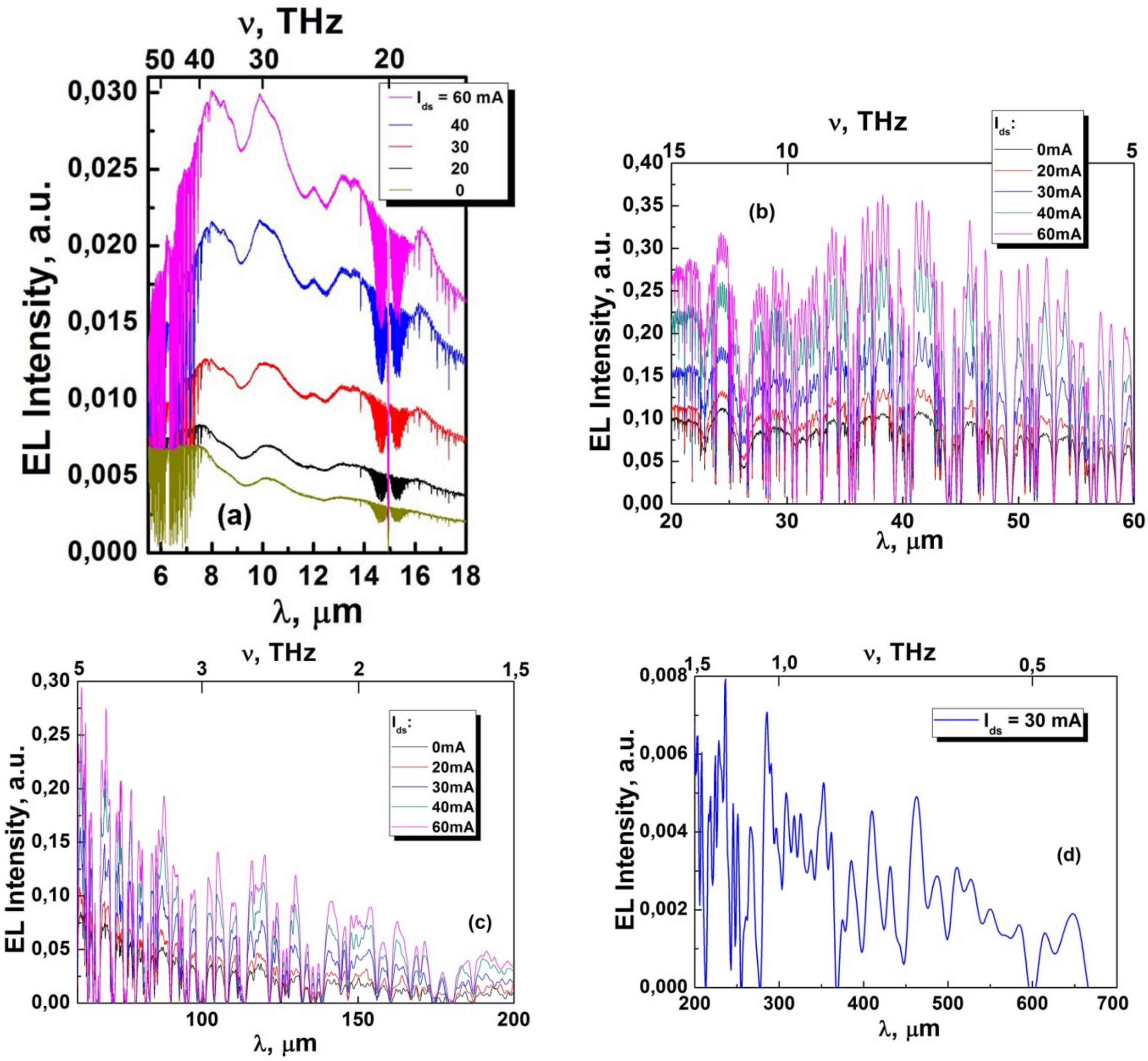

Fig. 3. The full spectra of THz irradiation generated by the therapeutic equipment "IR-Dipole" and "Infrateratron" at various operating currents. Spectra obtained using IR-Fourier spectrometer Bruker-Physik VERTEX 70

Manufactured by the principles described above, compact THz emitters are the basic elements of the "IR-Dipole" (Fig. 2b) and "Infrateratron" therapeutic equipment, which is successfully used in the treatment of several socially significant diseases [9]. The full spectrum of the THz irradiation generated by this equipment under the conditions of a stabilized drain-source current flowing through the SNS is shown in Fig. 3.

3. The use of THz emitters in pulmonology

One of the important applications of the created "IR-Dipole" apparatus is the practice in cardiac surgery to eliminate early pulmonary complications after surgery, for example, after aortocoronary bypass surgery [14]. It should be noted, that the development of pulmonary complications aggravates the condition of cardio surgical patients, requires additional therapeutic and diagnostic measurements, increases the pharmacological load, lengthens the length of hospital stay, and can lead to death. The effectiveness of the THz irradiation generated by the IR-Dipole apparatus for the treatment of patients with pulmonary pathologies was analyzed in detail at the V.A. Almazov National Medical Research Center (St. Petersburg). The goal of this work is to study the development of nosocomial pneumonia (NP) and ventilator-associated pneumonia (VAP) in patients in the early stages after cardiac surgery.

An observational retrospective open comparative study with pseudo-control ("case-control") was conducted based on the resuscitation department of cardiovascular surgery, which received patients after coronary artery bypass grafting and / or heart valve prosthetics. The study included patients with advanced complications in the form of focal infiltrative changes in the lungs (NP and VAP). Two groups were distinguished: the group in which, in addition to drug therapy, the exposure to the THz irradiation using the IR-Dipole apparatus on the Da-bao acupuncture point (RP 21) was performed, and the control group, which received standard treatment.

The early (on the first day) use of the THz irradiation allowed: to reduce the patient's stay in the intensive care unit by 4-8 days; reduce the radiological and pharmacological burden on the patient; reduce the time of intubation of the patient and finding him on mechanical ventilation by 4-8 days; increase the chances of favorable prognosis in patients with risk factors; start rehabilitation measures 4-8 days earlier. The comparative analysis of the effectiveness of the IR-Dipole apparatus for the treatment of pneumonia of different etiologies is given in Fig. 4a, b.

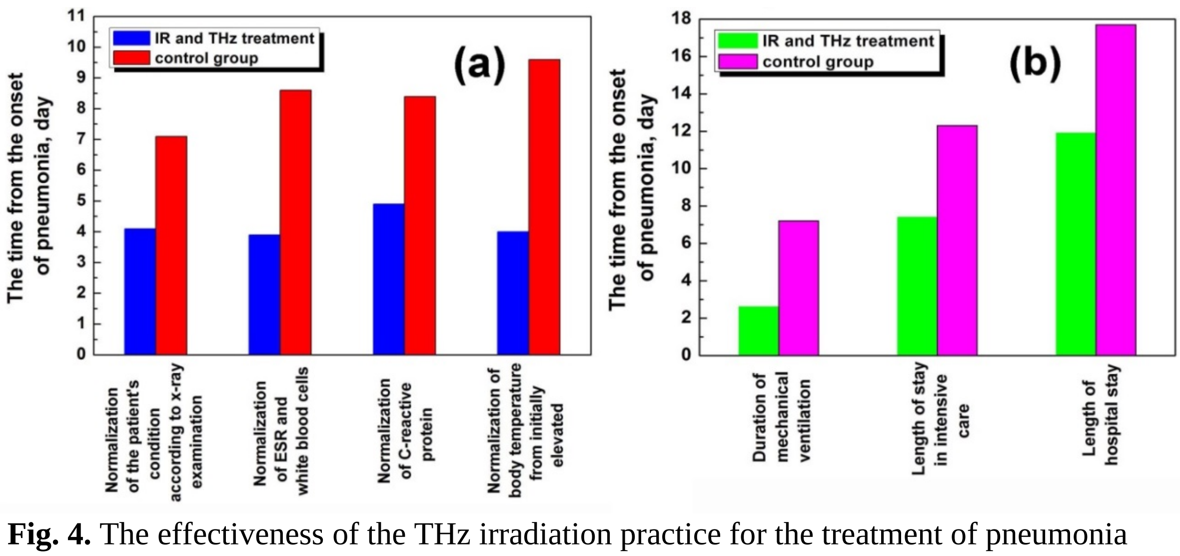

Fig. 4. The effectiveness of the THz irradiation practice for the treatment of pneumonia

The efficiency of using the THz irradiation is illustrated by the following clinical example. The patient is 64 years old. Diagnosis: Coronary heart disease. Atherosclerosis of the coronary arteries. Angina pectoris. Hypertonic disease. Operation 06/06/2012: sternotomy, mammary coronary artery bypass grafting, vein graft to the obtuse marginal artery, diagonal artery, right coronary artery, with cardiopulmonary bypass, and blood cardioplegia. 06/06/12 intraoperatively – a drop in hemodynamics, ventricular fibrillation. Resuscitation measures were carried out. The main stage of the operation had no features. The postoperative course is extremely severe, with cardiovascular and respiratory failure, metabolic disorders, pneumonia, and a septic state. From 06/10/12 to 06/15/12 was on mechanical ventilation. 06/13/12 Clinical, laboratory and radiological signs of bilateral lower-lobe pneumonia appeared. 06/13/12 antibiotic therapy has been started (according to the generally accepted scheme). During the discussion at the consultation, the THz-physiotherapy using the IR-Dipole device was added to the treatment. A change in key blood parameters during the treatment of pneumonia with the THz irradiation is presented in Table 1.

Table 1. A clinical example of a change in key blood parameters during the treatment of pneumonia with the THz irradiation

	ESR **mm/h** (normal 2-20)	**RBS** **10^{12} 1/L** (normal 4-5)	**WBS** **10^{9} 1/L** (normal 4-9)
Before treatment	41	3.66	28.7
2 days later	19	3.62	8.9
7 days later	10	4.10	8.7

4. Summary

All of the above indicates the prospect of using the THz irradiation for medical applications, including pneumonia caused by coronavirus. Since coronavirus causes SARS, with a predominant lesion of the alveoli, exposure to the THz irradiation can stimulate the protein activity of the cell, activate its protective mechanisms, and also prevent the virion from joining the cell receptor. Also, the THz irradiation results in the spin-dependent capture of oxygen to the iron ions in the hem, thereby facilitating its transport and the corresponding blood oxygenation (scarlet blood) [9].

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Compliance with ethical standards. *All procedures performed in a study involving people comply with the ethical standards of the institutional and / or national committee for research ethics and the 1964 Helsinki Declaration and its subsequent changes or comparable ethical standards.*
Informed consent was obtained from each of the participants in the study.

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