Generation of terahertz radiation in nanometer Ge - α-Sn - Ge films

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This paper presents the results of an experimental study of the generation of terahertz radiation in nanostructures based on nanometer Ge and α-Sn films, caused by a photocurrent induced by irradiation of nanostructures by ultrashort optical pulses. The objects under study were synthesized by hybridization of Sn layers with Ge, which made it possible to achieve unique properties of the obtained structures, which in fact represent a new class of topological materials. The results obtained in the course of experimental studies may indicate the generation of a photon drag current of nonequilibrium Dirac or Weyl electrons.

Introduction

With the dramatically increased technological capabilities in the field of synthesis of various micro and nanostructures in recent decades, the main tasks for experimental physicists have become research aimed at determining and discovering new magnetic, electronic, optical, and mechanical properties of newly synthesized materials. To date, a separate area has been formed in which various research groups around the world are engaged in the study of three-dimensional materials that have an electronic system with a linear spectrum, or rather topological insulators and Weyl semimetals, due to their unique properties, which allow the use of this class of materials in the field of electronics. nanophotonics, quantum computing. Accordingly, the creation and study of such systems is of undoubted interest.

More recently, it was shown that such compounds as TaAs, TaP, NbAs, NbP and $Bi_{1-x}Sb_x$ are Weyl semimetals [1-3]. It is also worth mentioning the Dirac semimetal based on an α-Sn film deposited on InSb (111) [4]. Over the past few years, a number of interesting works have been carried out in this area concerning theoretical proposals, the development of new materials, and the experimental study of the properties of these materials. A detailed generalization of the theoretical and experimental results of studying a number of Weyl semimetals can be found in the review [5]. Earlier in 1985, in theoretical work [6], the appearance of a metallic phase with a linear spectrum of an electronic system at the interface of two semiconductors Ge and α-Sn with an inverted band structure, forming a heterojunction, was demonstrated. In such semiconductor nanostructures, in a heterojunction, it becomes possible for Dirac electrons to appear, which have no mass and have tremendous mobility, which truly makes this system unique. The interaction of two-dimensional nanometer interfaces can lead to the appearance of the Weyl semimetal. The last works initiated the study of the electrical and optical properties of structures based on Ge and α-Sn nanometer films. In the present work, photon drag currents excited by femtosecond optical pulses and terahertz radiation induced by these photocurrents were observed in such nanostructures based on Ge and α-Sn nanometer films.

Experimental technique

The samples under study were nanometer-thick Ge and α-Sn layers grown on the surface of oxidized silicon. Using the method of electron-beam deposition, nanostructures were synthesized consisting of Ge and α-Sn layers of various thicknesses (1.5 ÷ 50 nm). The final synthesized nanostructure consisted of alternating layers of different nanometer thicknesses of germanium and gray tin, on top of which titanium contacts were deposited (Fig. 1).

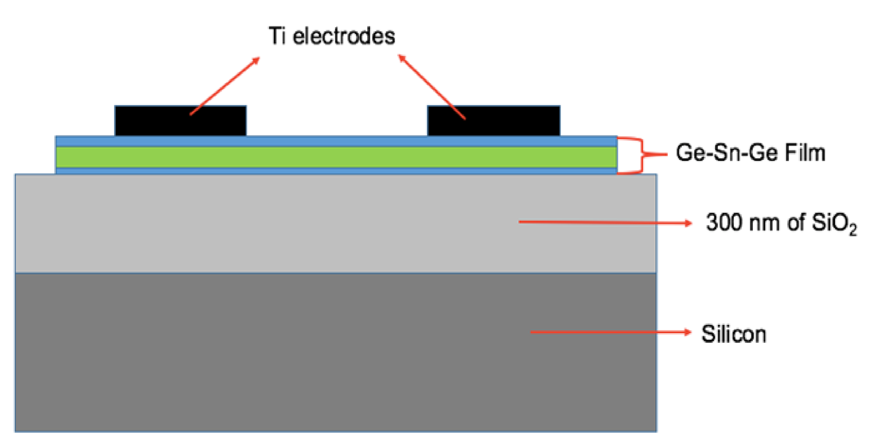


Fig. 1 — The structure of the test sample: upper Ge layer – 3 nm, Sn layer – 10 nm, lower Ge stabilization layer – 1.5 nm

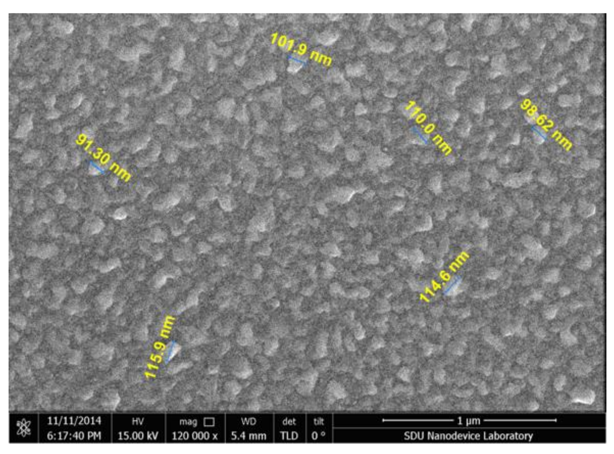


Fig. 2 — SEM image of the surface of the α-Sn film

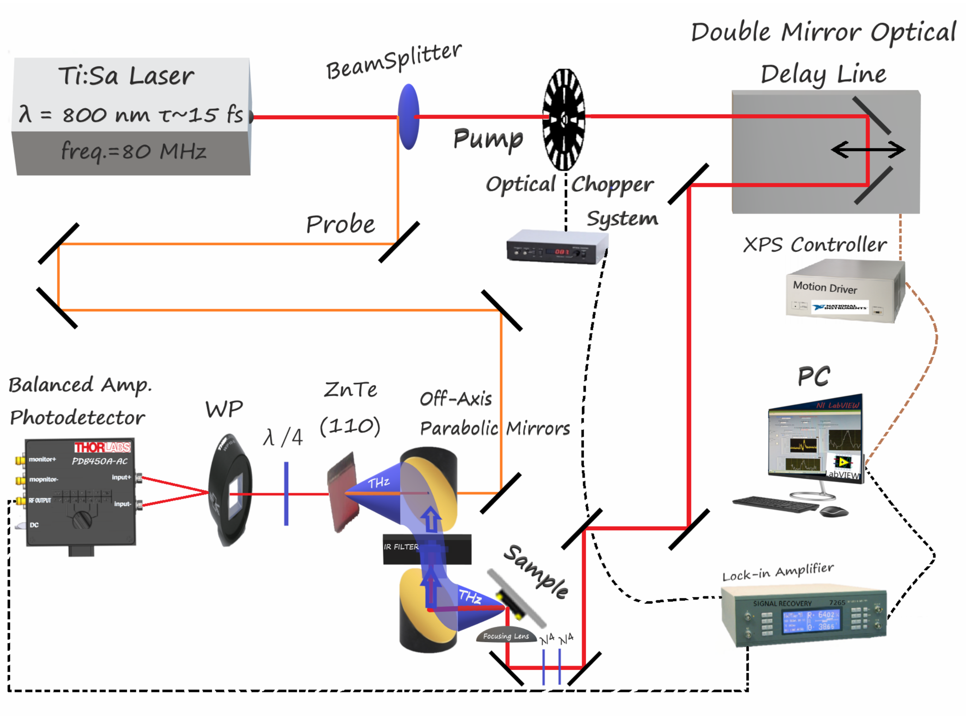


Fig. 3 — Experimental setup

To excite the samples, a Ti:Al_2O_3 laser was used. The laser work on wavelength 800 nm and generate pulses with a duration of 15÷100 fs. Photocurrents were recorded by measuring the photovoltage at contacts deposited on the upper surface of the sample. THz radiation was recorded using the method of electro-optical sampling in the specular reflection geometry (Fig. 3).

Results and discussion

Generation of THz radiation in samples based on a-Sn films

An investigation of the features of the generated THz radiation from samples with the Ge / α-Sn / α-Sn structure showed a pattern similar to the generation from bulk InAs, both for TE and TM polarizations. The amplitudes of THz pulses have the same sign when the polarization of the exciting light changes from TM to TE. In addition, for TE polarization, the amplitude is smaller.

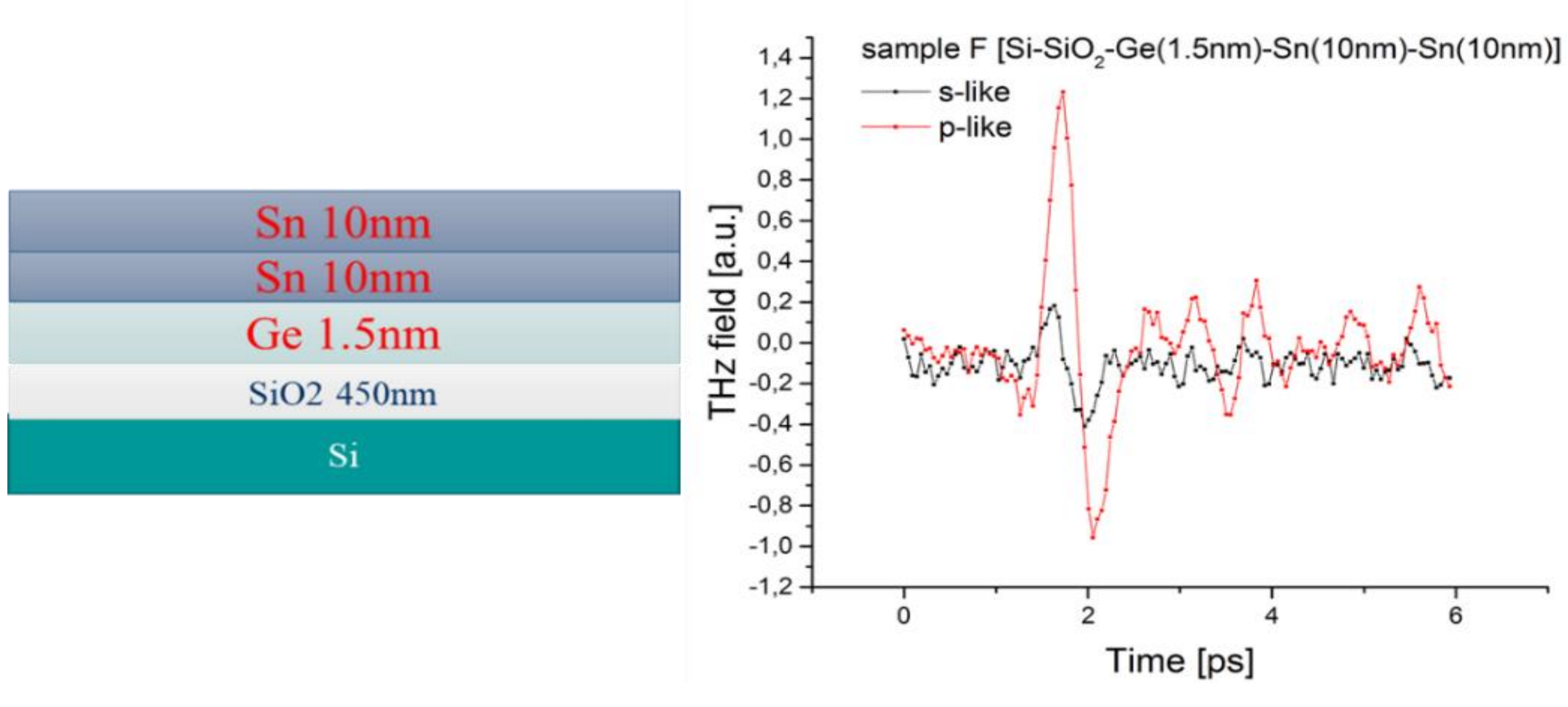


Fig. 4 — The structure of the test sample and the waveforms of the THz pulse

Generation of THz radiation in samples based on Ge films

For germanium films, experiments have shown similar results. The amplitude of THz radiation pulses with a change in polarization from TE to TM had the same sign, and a characteristic dependence of the THz pulse on the direction of the electric field vector was observed.

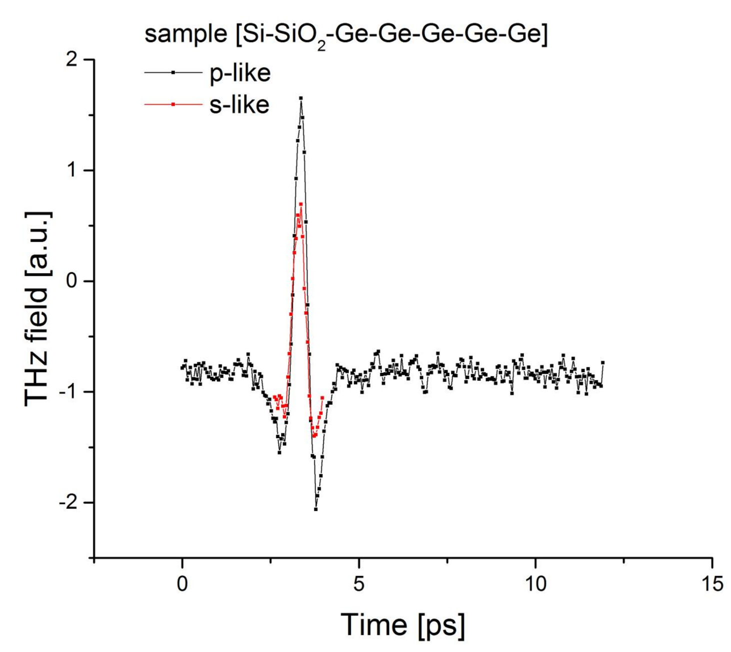


Fig. 5 — Waveforms of THz pulses (TM polarization)

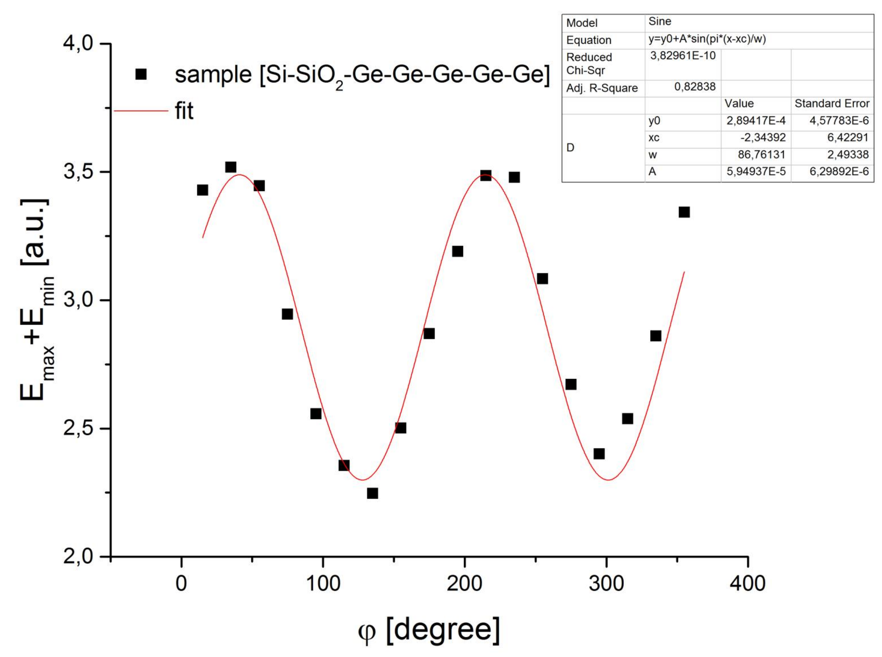


Fig. 6 — Dependence of the THz electric field (TM-polarization) on the direction of the polarization vector of the exciting light

Generation of THz radiation in samples based on Ge/α-Sn films

In the study of samples containing Ge / α-Sn heterojunction, completely different results were obtained. When the polarization of the exciting light changes from TM to TE, the amplitude of the THz pulse changes its sign. In addition, the amplitude of the THz pulse upon excitation by an optical pulse with TM polarization was negative in comparison with previous experiments. The dependence of the THz pulse amplitude on polarization is sinusoidal. For the p-component of the terahertz field, it is proportional to cos2φ, for the s-component of the terahertz field – sin2φ (Fig. 12). When the direction of light propagation was changed, an inversion of the sign of the THz pulse was observed. The dependence of the maximum pulse amplitude on the intensity of the exciting light was linear. Experiments on studying photocurrents by the contact method showed a similar behavior of the corresponding dependences. Thus, the experimentally observed dependences of the photocurrent on the polarization of light, the direction of the wave vector, and the intensity of the excited light are inherent in the photon drag current.

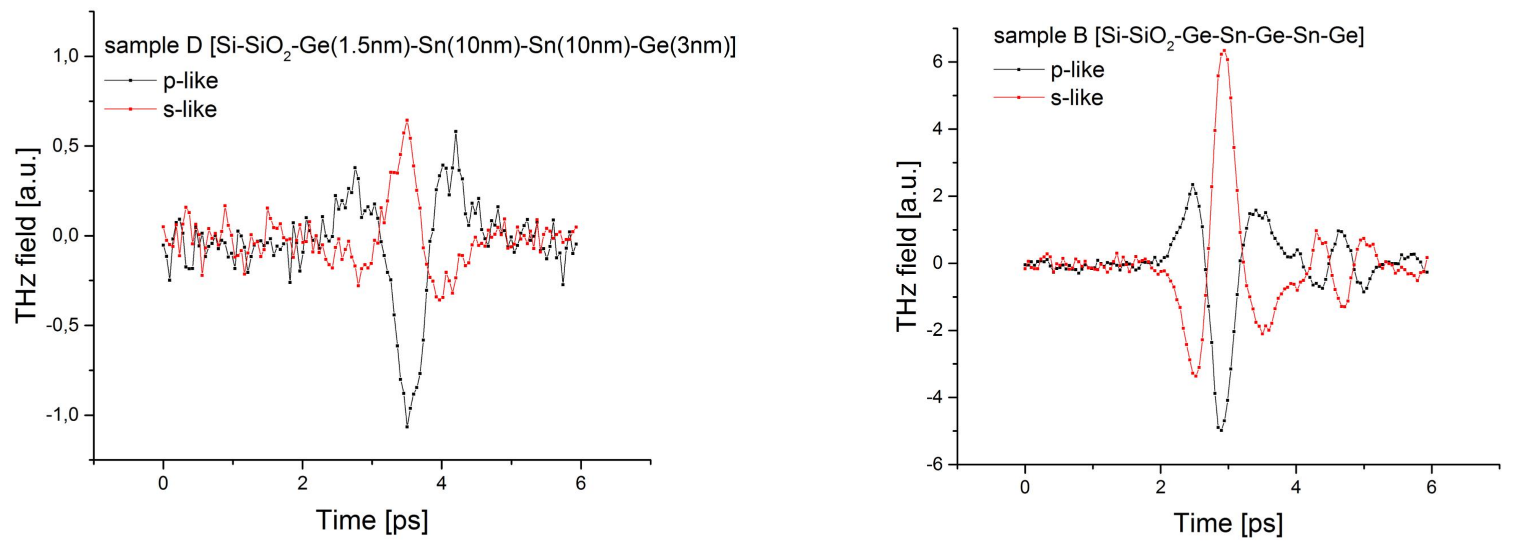


Fig. 8 — Waveforms of THz pulses:
on the left – Si/SiO_2/Ge/α-Sn/a-Sn/Ge; right – Si/SiO_2/Ge/α-Sn/Ge/α-Sn/Ge)

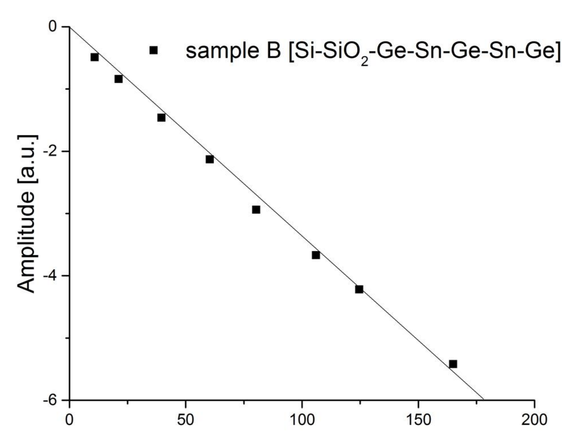


Fig. 9 — Dependence of the THz pulse amplitude on the average light power

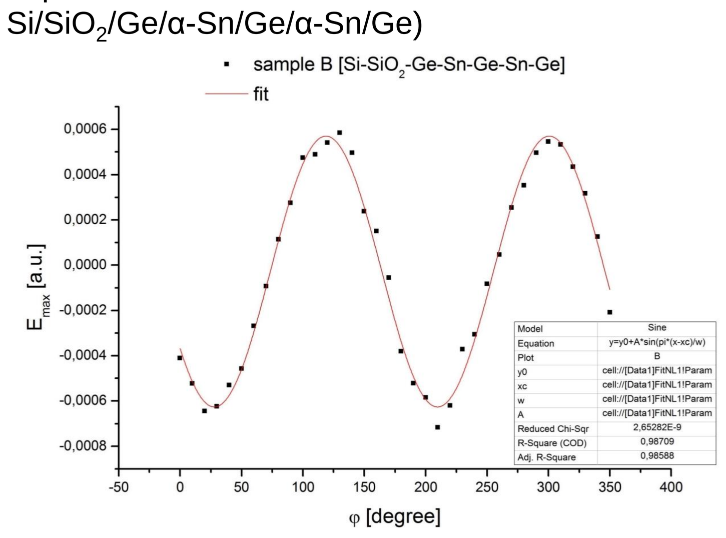
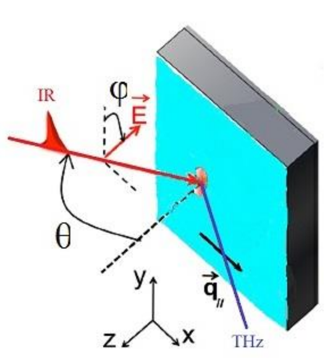


Fig. 10 — Dependence of the amplitude of the THz electric field (TM-polarization) on the direction of the polarization vector of the exciting light



$$j_i = \chi_{ijkl}(E_j E_k + E_k E_j)/2q_l$$
$$j_x = \sin\theta(a + 2b\cos^2\theta + 2b\cos^2\theta\cos 2\varphi)$$
$$j_y = b\sin 2\theta \sin 2\varphi$$

Fig. 11 — Scheme of the experiment

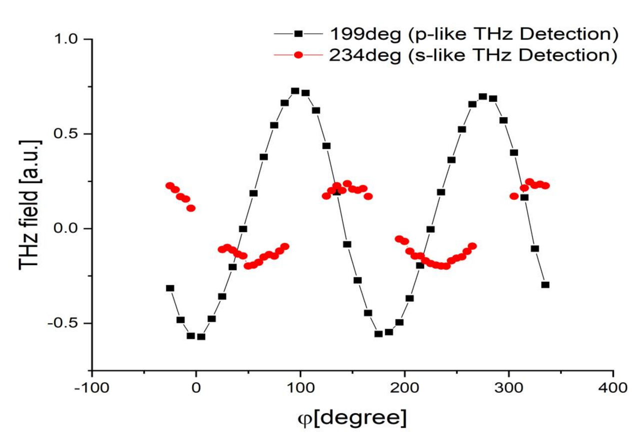


Fig. 12 — Dependence of the THz electric field amplitude (TM polarization, TE polarization) on the direction of the polarization vector of the exciting light

Conclusion

This paper reports on the observation of photon drag currents of nonequilibrium Dirac or Weyl electrons in nanostructures based on Ge and α-Sn films and terahertz radiation induced by these photocurrents. At the microscopic level, the nature of the THz generation process in the samples under study based on nm-sized films of α-Sn / Ge / α-Sn is apparently due to the appearance of asymmetry in the momentum space of nonequilibrium Dirac electrons during interband transitions.

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