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Manifestation of the electric field screening effect in the process of generation of terahertz radiation in $p-n$-heterostructures a-Si:H/a-SiC:H/c-Si at photoexcitation by ultrashort laser pulses

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Data are presented on the manifestation of the strong influence of the electric field screening effect in $p-n$-heterostructures a-Si:H/a-SiC:H/c-Si on the properties of generated THz radiation in such structures under conditions of interband photoexcitation by femtosecond laser pulses. Screening of the field in the structure by nonequilibrium charge carriers at high pump intensity leads to a change in the direction of the electric field of the generated THz electromagnetic wave, which manifests itself as a change in the polarity of the pulse of the detected THz-signal. The change in signal polarity can be associated with a change in the direction of the fast component of the photocurrent in the structure responsible for THz-generation. A change in the polarity of the THz-radiation pulse is observed both with a change in the photoexcitation intensity and with a change in the bias voltage

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It is common knowledge that subpicosecond pulses of terahertz (THz) electromagnetic radiation containing several cycles of electromagnetic oscillations are produced under photoexcitation of both bulk semiconductors and semiconductor structures by femtosecond laser pulses [1,2]. The mechanism of this THz-generation is associated with the excitation of a fast dipole moment or a short photocurrent pulse in the material or structure. The amplitude of electric field of the generated electromagnetic wave in the far field (at a THz-detector) is proportional to the second time derivative of dipole moment or the first derivative of photocurrent produced by femtosecond laser radiation [3]. The technique of THz-generation with femtosecond laser pulses is used widely in THz-time domain spectroscopy (THz-TDS) and THz-visualization of a wide variety of objects [4]. Both the amplitude and phase of an electromagnetic wave are measured in such spectroscopy experiments, which distinguishes them from traditional spectroscopy methods based on measuring the intensity of radiation [4].

Silicon structures were used in the first study into the generation of THz-radiation under interband photoexcitation of $p-n$-structures by femtosecond laser pulses [5]. The effect was attributed to the acceleration of photoexcited carriers in the strong built-in electric field of the structure and, accordingly, the formation of a short burst of large-amplitude photocurrent. A comparatively high efficiency of such THz-generation was noted. A number of studies into THz-generation in heterostructures with $p-n$-junctions based on A_3B_5 semiconductors have also been performed [6–9]. A certain influence of the effect of screening of the built-in electric field by nonequilibrium charge carriers on THz-generation was noted.

In the present study, we report the results of examination of THz-generation under interband photoexcitation of $p-n$-heterostructures based on a-Si:H/a-SiC:H/c-Si by ultrashort laser pulses. THz-radiation in such structures has already been detected in [10,11]. The data obtained in the present study are indicative of a strong influence of the electric field screening (EFS) effect in $p-n$-heterostructures on the properties of generated THz-radiation. EFS by nonequilibrium carriers at high photoexcitation intensities (high pump intensities) may even lead to a change in direction of the fast component of total photocurrent that drives THz-generation. This, in turn, manifests itself in a change in polarity of a pulse of generated THz-radiation (in other words, it is manifested as a 180° phase shift of the electric field of a THz electromagnetic wave).

The studied $p-n$-heterostructures based on a-Si:H/a-SiC:H/c-Si were similar to those investigated in [10]. In essence, they were heterojunction (HJT) solar cells [12]. The composition of these structures (starting from the top surface onto which pump laser radiation was incident) was as follows: a layer of ITO (indium tin oxide) with a thickness of 100 nm, a (p) a-Si:H layer doped with boron to a level of $10^{19}\,\mathrm{cm}^{-3}$, intrinsic ($i$) a-Si:H and (i) a-SiC:H layers, an n-type [100] Si substrate with a resistivity of $1.5\,\Omega\cdot\mathrm{cm}$ and a thickness of $140\,\mu\mathrm{m}$, (i) a-SiC:H and (i) a-Si:H layers, and a (n) a-Si:H layer doped with phosphorus to a level of $10^{21}\,\mathrm{cm}^{-3}$ and also coated with 100 nm of ITO (bottom surface of

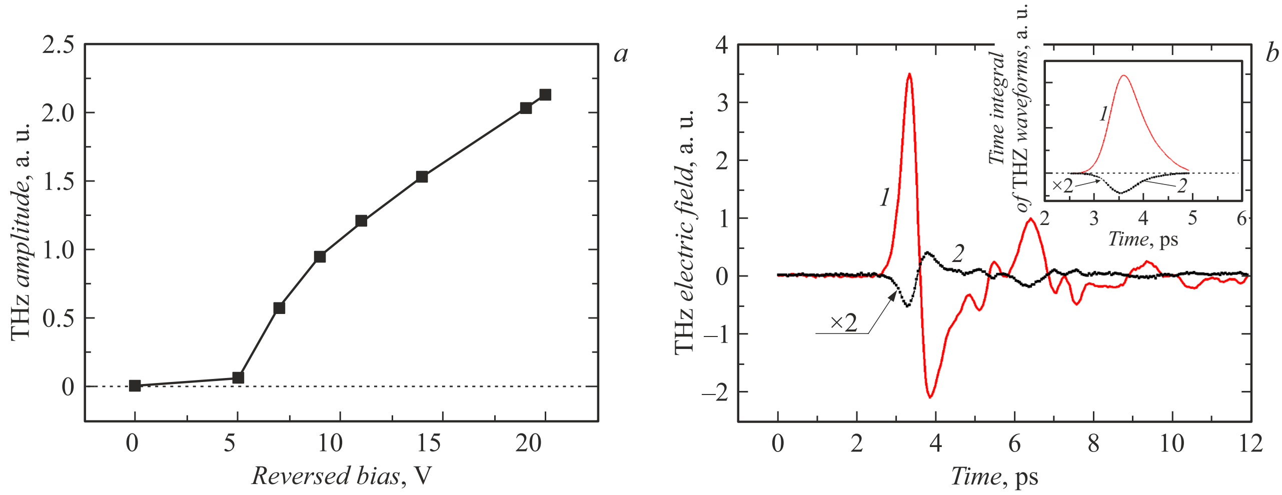

Figure 1. *a* — Dependence of the amplitude of a THz-radiation pulse generated in the *a*-Si:H/*a*-SiC:H/*c*-Si *p*—*n*-heterostructure on the reverse bias voltage at an average excitation radiation power of 16 mW (the dependence for the first positive maximum of the THz waveform is plotted (see panel *b*). *b* — Characteristic waveforms of THz-radiation at a reverse bias voltage of 14 V and average photoexcitation powers of 52.8 (*1*) and 222 mW (*2*). The inset shows the time integrals of THz waveforms within the first THz-radiation pulse (within the 2.4—4.9 ps time interval) that reflect the shape of fast photocurrent pulses.

the structure). The total thickness of amorphous layers on the front and back sides of the structure was 26 nm. The difference between the samples studied here and the structures examined earlier in [11] was in the lack of a silver current-collecting grid on the surface of ITO layers. Samples 10 × 10 mm in size were used for measurements. A reverse bias voltage was applied to the structures. A point contact of silver paste with a diameter on the order of 2—3 mm was applied for this purpose to the top ITO layer (with which the top electrode was in contact). The bottom electrode was a massive brass holder. The entire sample was secured on it with silver paste that was in contact with the bottom ITO layer.

A femtosecond titanium-sapphire laser with an emission wavelength of 800 nm, an approximate laser pulse duration of 15 fs, and a pulse repetition rate of 80 MHz was used to excite THz-radiation. Excitation radiation was incident at an angle close to 45° on the structure under study (*p*-polarization was used) and was focused onto the surface of the top ITO layer into a spot with a size on the order of 250 μm. The average photoexcitation power in the experiments discussed here varied from 5 to 220 mW. THz-radiation generated in the structure was collected in the direction of specular reflection from the input surface of the structure by parabolic mirrors and transported to a THz-detector. THz-radiation was detected using the method of electro-optics sampling [13] of THz waveforms in a (110) ZnTe crystal with a thickness of 1 mm. This method allows one to measure both the amplitude and phase of the electric field of pulsed THz-radiation. A detailed description of the experimental setup was provided in [14].

A THz-radiation signal is produced when a reverse bias voltage (RBV) is applied to the structure, and the amplitude of this THz-signal increases with increasing bias at relatively low pump intensities (Fig. 1, *a*). The growth of amplitude of the THz-signal with increasing RBV is attributable to an increase in both the acceleration and the velocity of motion of non-equilibrium carriers in the *p*—*n*-junction field, as well as to an expansion of the region in which this field is concentrated. The amplitude of both the total photocurrent and its fast component (fast photocurrent) increases as a result, and the amplitude of the generated THz electromagnetic wave field also increases accordingly.

Figure 1, *b* shows the characteristic waveforms of THz radiation generated in the studied *p*—*n*-heterostructure at an RBV of −14 V and two values of the average pump power that differ by a factor of almost 4. It is evident that with a strong increase in pump power, the THz-radiation signal gets weaker and even changes polarity. The THz-pulse polarity reversal indicates that the fast photocurrent, which drives THz-generation, has the opposite direction at high pump power. The inset also shows the time integrals of THz waveforms, which may be used to assess the shape of fast photocurrent pulses. It can be seen that the fast photocurrent does indeed change polarity at high pump power.

Thus, while the direction of fast photocurrent at low pump intensity is set by the direction of the electric field in the reverse-biased *p*—*n*-junction, the direction of fast photocurrent at high pump intensity is opposite to this field. This behavior of photocurrent may be associated with strong EFS by the charge of non-equilibrium carriers produced by intense interband pumping in the *p*—*n*-structure. At subpicosecond timescales corresponding to the process of generation of observed THz-radiation, carriers produced by intense pumping have insufficient time to go into the contacts, accumulate in the structure and at its heterointerfaces, and induce a field that compensates for the field of the

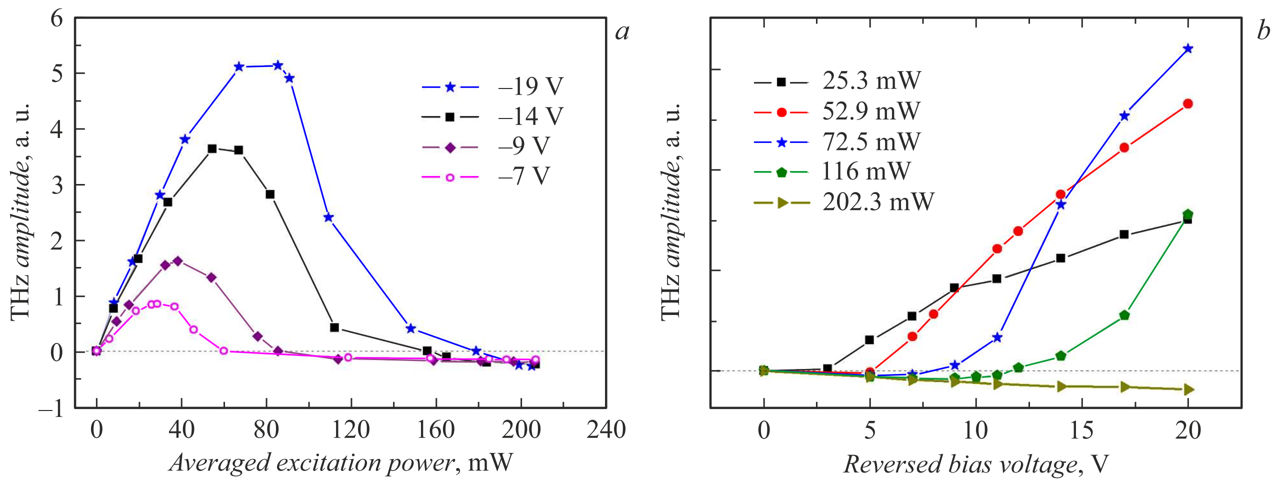

Figure 2. *a* — Dependence of the amplitude of the first (main) THz-radiation pulse generated in the *a*-Si:H/*a*-SiC:H/*c*-Si *p*–*n*-heterostructure on the average photoexcitation power at different reverse bias voltages at the structure. *b* — Dependence of the amplitude of the main THz radiation pulse on the reverse bias voltage at the structure at different values of average pump laser power. The dotted line corresponds to the zero signal level.

p–*n*-junction. Apparently, the structure then turns out to be effectively forward-biased, the total photocurrent decreases, and its fast component is inverted. It is possible that a high repetition rate of pump pulses plays an important role in the accumulation of charge in the structure. As a result, the fast photocurrent may decrease, become zero, and even change polarity as the intensity of photoexcitation increases.

Figure 2, *a* shows the dependences of amplitude of the first THz-radiation pulse on the average pump power at different reverse bias voltages. It can be seen that these dependences are non-monotonic with the maxima positions depending on the RBV (the higher the RBV, the higher the pump intensity at which the maximum THz-pulse amplitude is achieved). The signal drops to zero beyond the maxima. The pump intensity at which the THz-signal vanishes also increases with increasing RBV. As the pump intensity increases further, the THz-signal changes sign, and its amplitude increases slowly. These trends are illustrative of the effect of EFS by non-equilibrium charge carriers in the *p*–*n*-structure in the process of generation of THz-radiation.

Figure 2, *b* shows the dependences of amplitude of the main THz-pulse on the reverse bias voltage at several values of the average photoexcitation power. The observed patterns may also be attributed to the EFS effect in the *p*–*n*-structure. At a relatively low average pump power (on the order of 25 mW), when the screening effect is insignificant, the THz-signal amplitude increases with increasing RBV at the structure, since the amplitude of fast photocurrent, the direction of which is set by the field of the *p*–*n*-junction, also grows in this case. At high pump powers (in the present case, 202 mW and higher), when the electric field in the structure is apparently screened to a significant extent within the entire examined RBV range, the accumulation of carriers is observed, the structure turns out to be effectively biased in the forward direction, and the THz-signal changes polarity. It can be seen from the figure that the signal amplitude increases slightly with an increase in voltage applied to the structure. In the region of intermediate values of the average power of pump radiation (at an average power on the order of 52–116 mW), when significant EFS in the structure is observed only at relatively low bias voltages, the THz-radiation pulse changes polarity with an increase in RBV (Fig. 2, *b*). It is precisely this effect in THz-generation that has been observed earlier in [10] for similar structures.

The EFS effect is manifested clearly in the behavior of amplitude and polarity of the observed THz-radiation pulses (see above). However, the influence of this effect on the THz-radiation spectrum is insignificant. EFS in the structure leads only to a slight change in the ratio of amplitudes of the frequency comb peaks corresponding to the internal reflections of THz-radiation in the structure: under the conditions of EFS, the ratio of amplitudes of neighboring peaks varies more slowly with increasing frequency (see, e.g., [10]).

Apparently, the resistance of electrical contacts, which act as series resistances in the structure/voltage source circuit, is an important factor in the observed EFS effect in *p*–*n* *a*-Si:H/*a*-SiC:H/*c*-Si heterostructures. When the resistance of contacts to the structure is not low enough (as in the case of point contacts to ITO: droplets of silver paste applied to ITO layers), the effect is particularly pronounced. If the contact resistance is low (as, e.g., in the case of *p*–*n* heterostructures studied in [11]) with a silver contact grid applied to the top and bottom ITO layers (extended contacts to ITO), the EFS effect is insignificant. Only a slight non-monotonicity was observed in the dependence of the generated THz-radiation pulse amplitude on the average photoexcitation power [11].

Thus, the specific features of THz-radiation generation in $p-n$-heterostructures based on a-Si:H/a-SiC:H/c-Si under reverse bias and interband photoexcitation by femtosecond laser pulses were studied. It was found that EFS in the $p-n$-heterostructures exerts a strong influence on the properties of generated THz-radiation at high pump intensity. Apparently, screening of the field by non-equilibrium carriers may induce a change in direction of fast photocurrent driving THz-generation, thus leading to a change in polarity of the generated THz-radiation pulse. The THz-radiation pulse polarity changes when both the photoexcitation intensity and the bias voltage are varied. It seems that the resistance of contacts to the structure is very important in this context. In the case of low contact resistance (structures with a silver contact grid applied to the top and bottom surfaces of the structure), the screening effect is insignificant.

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Conflict of interest

The authors declare that they have no conflict of interest.

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