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Optics

Silicon lenses with HDPE anti-reflection coatings for low THz frequency range

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Abstract. Presented in this paper have been the design, fabrication, and testing of the high resistance floating-zone silicon (HRFZ-Si) optics with the anti-reflection (AR) high-density polyethylene (HDPE) coatings, for the low part of terahertz (THz) frequency range ($\nu \approx 0.14$ THz), by using the precision press molding. Experimental results of the transmission of the wafers and lenses with double-sided anti-reflection HDPE coatings for radiation frequency 0.14 THz showed an increase in the transmittance T values up to ≈1.45 times as compared to T magnitudes in wafers and lenses without HDPE coatings. The capability to use terahertz lenses with HDPE interference films and the technology of press molding, as a cheaper alternative to the horn antenna applications for the terahertz range of 0.14 THz was shown. With advancements in THz imaging and 6G communication technologies, further implementation of these Si optical elements is possible.

Keywords: HRFZ-Si lens, anti-reflection HDPE coatings, THz applications.

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1. Introduction

For THz imaging and signal transmission applications, the widely used horn antennas demonstrate good pattern characteristics at certain sub-THz and THz frequencies, but their fabrication is rather cost ineffective even at the low part of the THz radiation frequency range ($\nu \approx 0.1\ldots0.3$ THz) and they become difficult to manufacture for higher THz frequencies. As well, frequently used planar antennas in THz sources and detectors demonstrate poorer directivity, because of broad beam patterns. For the THz imaging and wireless transmission (*e.g.*, 6G systems), together with high directionality, significant is the small space consuming of the THz optical elements and, at the same time, the irrelative effectiveness in controlling the propagation of radiation beams. Because of this, the development of space effective and cheap optical elements becomes important. The THz applications require some cost-effective additional “optical” elements to improve compactness and increase the efficiency of THz sources or radiation coupling detectors.

A desirable solution to these problems is fabrication of small-size THz optical antenna elements (lens antennas), which, perhaps, can have not so good pattern characteristics but are cost-effective in fabrication and can be easily assembled in arrays with characteristics that are satisfactory in many applications. To choose optical elements for the THz range, they should have low absorption coefficients, a relatively high index of refraction to reduce the thickness and curvature of lens surfaces and have low Fresnel losses.

Plenty of plastics are transparent in the THz range and can be used for fabrication of THz optical elements. However, as a rule, they have low dielectric permittivity (low index of refraction). That leads to the need of increasing the thickness and curvature of lens surfaces to be used and does not allow fully concentrate of the THz radiation on, as a rule, small area THz detectors. The lenses fabricated from high permittivity (high index of refraction) materials allow a much better concentration of the THz radiation but have high Fresnel losses. Therefore, to decrease Fresnel losses for effective application as THz optical elements, there can be used transparent materials with a high index of refraction but coated with lower permittivity anti-reflection highly transparent plastic, or wide-band semiconductor layers of a certain thickness.

As the basic material with a low absorption coefficient α (up to $\alpha < 0.5$ cm^{-1}) in the THz range, there can be used the HRFZ-Si having a resistivity $\rho \sim 10$ kΩ·cm [1] (in our case HRFZ-Si had $\rho > 20$ kΩ·cm). At the same time, HRFZ-Si in the THz range has high dielectric permittivity (ε_{Si} = 11.7) and thus, a high index of refraction ($n_{Si} = \sqrt{11.7} = 3.42$). Then, to reduce Fresnel losses from Si wafers or lenses, one should choose the material for covering Si surfaces by low absorbing materials with proper lower dielectric permittivity and thickness to make AR layers. HRFZ-Si has a low absorption coefficient up to room temperatures in the THz range, which allow for the pair of HRFZ-Si and the material with a lower refractive index and low absorption coefficient, minimize the thickness and curvature of optical elements. Moreover, the Si index of refraction is achromatic, and it does not depend on the orientation of the crystallographic axes.

The lenses from HRFZ-Si have been widely used for continuous-wave and pulsed terahertz (THz) imaging, astronomical applications, *etc*. [2–7]. However, the high dielectric permittivity of HRFZ-Si results in a significant impedance mismatch with air, which can lead to a loss of transmission T up to 46% [8].

An anti-reflection coating (ARC) is used as means of suppressing the reflectivity of electromagnetic radiation from surfaces of the wafers or lenses. The main condition for the increase of passing the useful output power from the sources through the silicon surfaces depends upon that how suitable the thin film's refractive index is to the required value, as well as the low amount of radiation losses in the film. In this case, for optical elements with AR layers, the transmittance can be noticeably increased due to the interference phenomena. The total power front surface reflection from an optical element at normal incident radiation of wavelength λ can be made equal even to zero [9], if

$$n_{AR} = \sqrt{n_{\text{Si}}}\,, \qquad (1)$$

$$d_{AR} = \frac{(2m+1)\lambda}{4n_{AR}} \;\; (m = 0, 1, 2, ...), \qquad (2)$$

where n_{AR} is the refractive index of the AR layer and n-Si is the refractive index of the optical element (*e.g*., from silicon), d_{AR} is the thickness of the coating AR layer. The thickness of the AR layer can be any odd number of quarter wavelengths, and typically, is $\lambda/4n_{AR}$ thick to minimize the reflection effects. From Eq. (1), it is seen that the dielectric permittivity of the AR coating material at normal radiation incidence should be $n_{\text{ideal}} = n_{AR} = \sqrt{n_{\text{Si}}} = \sqrt{3.42} = 1.849$ for HRFZ-Si lenses and wafers, where n_{Si}= 3.42 is the index of refraction of HRFZ-Si. At this n_{ideal} = 1.849 index of refraction, the minimal thickness of the interference film for λ = 2.14 mm (0.14 THz) is d_{AR} = 289 µm. However, in the THz spectral region, there are almost no highly transparent materials with such a rather high index of refraction ($n_{AR} \approx 1.85$) to satisfy the requirements (1) and (2). For most transparent materials in the THz radiation frequency range, the index of refraction n is less (*e.g*., for polymeric materials in low frequency THz range typically $n \sim 1.4…1.8$ [10]) as compared to ideal $n_{AR} \approx 1.85$. In this case, the surface reflection will be not zero, but still the maximum transparency level will be high enough but at the coating thicknesses shifted to thicker films defined by Eq. (2). The estimated difference in the transparency of the system (Si + *e.g*., polymeric material) will be small as compared to the ideal case (see below).

There have been a number of publications on different types of ARC or Si lenses, such as, *e.g*., a thick dry epoxy film sheet photoresist SUEX ($n \approx 1.75$), which was conformally coated 1-cm-diameter Si lenses [11] or vacuum-deposited Parylene polymers ($n = 1.62$) as ARC for HRFZ-Si lenses [12]. Although these methods are effective, they require complicated control for technological processes, for example, such as the reflow of the relatively thin SUEX layers.

Other plastics like to Mylar ($n_{\text{Mylar}} \approx 1.73$ in low frequency THz range [10] and Kapton ($n_{\text{Kapton}} \approx 1.88$ [13]) are also potential candidates for anti-reflection coatings of Si-based optical elements in the THz range. Moreover, $n_{\text{Kapton}} \approx 1.88$ is close to the required value $n_{\text{ideal}} = n_{AR} \approx 1.85$. However, such materials may be difficult to apply to small area curved optical components, such as Si lenses. Moreover, Mylar films have several times larger absorption coefficient α as compared to α ($\alpha < 2.5$ cm^{-1}) in HDPE in low frequency THz range and are more difficult to fabricate at the thickness of hundreds micrometers for THz range.

A number of technologies in application to ARC, namely: the direct machining of mixed epoxies, laser machining, deep reactive ion etching, have been described, *e.g*., in [14]. Although these methods are effective, they require rather specialized fabrication tools. Today, the search for new materials and technologies to reduce reflection losses in silicon lenses is continued.

A hybrid structure of single-crystal HRFZ-Si and the high-density polyethylene (HDPE) layers have been successfully used for infrared (IR) lenses coatings by using precision press molding [15]. The results of testing showed that the IR transmittance of these hybrid structures is higher than that of Si itself in some regions of wavelength. Englert [16] has reached success in coating both sides of silicon windows by using 20 µm of the low-density polyethylene (LDPE) (n_{LDPE} = 1.51 [17]) to achieve AR performance in the THz range at λ = 118 µm.

Nevertheless, although HDPE and LDPE coatings have been successfully applied, this technique, to our knowledge, has not been demonstrated for the THz radiation frequencies below 1 THz. From the viewpoint of the mechanical and thermal stability properties, the products from HDPE are preferable as compared with those from LDPE. The refractive index n_{HDPE} = 1.54…1.585 [6, 9, 13] > n_{LDPE} = 1.51 [17] in the low frequency THz range with similar transparency characteristics.

For radiation frequency ν = 0.14 THz, the maximum transparency level of Si optical elements with interference coatings corresponds to the thickness of the HDPE coating film $d_{HDPE} \approx 348$ µm, which allowed using the standard thickness of HDPE films with the next processing and technology of pressure procedures. It significantly reduces the cost of THz optical elements. Important is the fact that the refractive index of HDPE is achromatic in a wide frequency range [10].

Here, it is presented the method for ARC formation to Si wafers and lenses with a matching layer of HDPE. The technique uses pressure and heating at low temperatures to couple the coating and wafers or lenses by using a thin glue layer. A purpose-built construction enables one to coat strongly curved lenses from both sides. This technique is fully scalable to larger lenses or wafers, limited only by the material availability and appropriate tooling.

The HDPE-coated lenses were optimized for the frequency sensitivity of a THz source at 0.14 THz. The transmission of silicon wafers and lenses in this radiation frequency range is $T \approx 50\%$. The HDPE coatings were used to noticeably increase the transmittance of the optical elements with transmission peaks by ≈1.45 times. One of the reasons to choose HDPE as coating AR material for Si lenses or wafers was that their refractive indexes are achromatic in the wide frequency range.

2. Modeling of anti-reflection coating

The optical reflection and transmission of single-layer ARC were widely described (see, *e.g.*, [18–20]). The incident plane electromagnetic wave falls down at an angle θ_0 from the free space (air) on a surface of the substrate that is covered by the thin-film AR layer. Shown in Fig. 1 is the schematic view of the optical reflection and transmission of radiation by flat surfaces in the two-layer structure with ARC, where n_0, n_1, n_m are the refractive indexes and θ_1, θ_m are the refractive angles, while d_1 is the thickness of AR layer.

In an optical absorbing media, the reflectance R_{ARC} of the thin-film layer with a refractive index n_1 and thickness d_1 (Fig. 1) is [21]:

$$R_{ARC} = \frac{(\eta_0 - \eta_m)^2 \cos^2(\delta_1) + \left(\frac{\eta_0\eta_m}{\eta_1} - \eta_1\right)^2 \sin^2(\delta_1)}{(\eta_0 + \eta_m)^2 \cos^2(\delta_1) + \left(\frac{\eta_0\eta_m}{\eta_1} + \eta_1\right)^2 \sin^2(\delta_1)}, \quad (3)$$

where δ_1 is the phase factor:

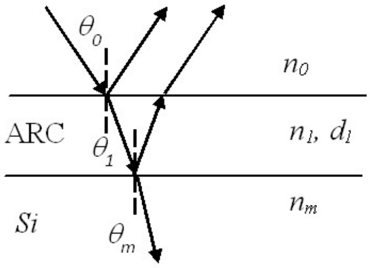

Fig. 1. The schematic view of the optical reflection and transmission of the radiation falling down from the air on the flat surfaces of the two-layered structure (ARC + Si).

$$\delta_1 = \frac{2\pi n_1 d_1 \cos(\theta_1)}{\lambda}, \quad (4)$$

λ is the radiation wavelength in the free space, θ_1 is the angle of refraction.

The parameters η_0, η_1, η_m are the tilted optical admittances of the incident radiation in the free space falling down onto thin film and substrate media, respectively. They are dependent on wave polarization.

For *s*-polarization:

$$\eta_0 = Y_0 n_0 \cos(\theta_0), \ \eta_1 = Y_0 n_1 \cos(\theta_1), \ \eta_m = Y_0 n_m \cos(\theta_m), \quad (5)$$

and for *p*-polarization:

$$\eta_0 = Y_0 \frac{n_0}{\cos(\theta_0)}, \ \eta_1 = Y_0 \frac{n_1}{\cos(\theta_1)}, \ \eta_m = Y_0 \frac{n_m}{\cos(\theta_m)}. \quad (6)$$

Here, Y_0 is the free space admittance.

To agree with the Snell law:

$$n_0 = \sin(\theta_0) = n_1 \sin(\theta_1) = n_m \sin(\theta_m). \quad (7)$$

Shown in Fig. 2 are the dependence of the transmission coefficients $T_{ARC} = 1 - R_{ARC}$ of the structures Si/ARC at the first boundary of Si wafer. These dependences are presented for thicknesses of HDPE coating films with $n_1 = n_{HDPE} = 1.54$ [17] and the virtual (ideal) coating film with the coefficient of refraction $n_1 = n_{\text{ideal}} = n_{opt} = 1.85$, which satisfies the request for the largest light transmission at its normal incidence (Eq. (1)). One can see that for the value of n_{HDPE}, which is smaller as compared to n_{opt}, the maximum in the transmission coefficient is lower, and it is shifted to the larger ARC thickness values, though the transmission is relatively high (≈97%). The first maximum of the transmission coefficient corresponds to the thickness of the HDPE film $d_{HDPE} = 348$ μm. This value, which is larger as compared to the ideal coating layer $d_{opt} = 289$ μm, was taken as the starting point for estimations of the transmission coefficients for Si lenses and wafers with HDPE coatings.

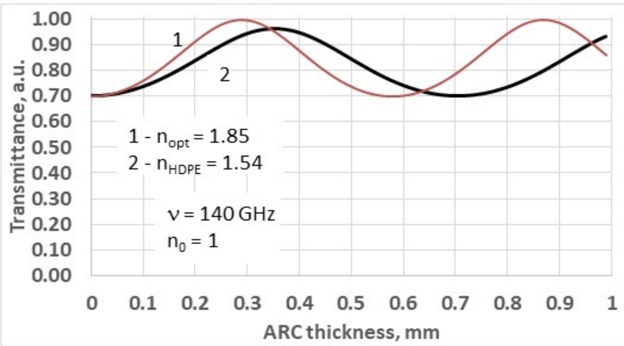

Fig. 2. Calculated dependences of the transmission coefficients for the first boundary of the ARC/Si structure: $n_{HDPE} = 1.54$, $n_{opt} = 1.85$.

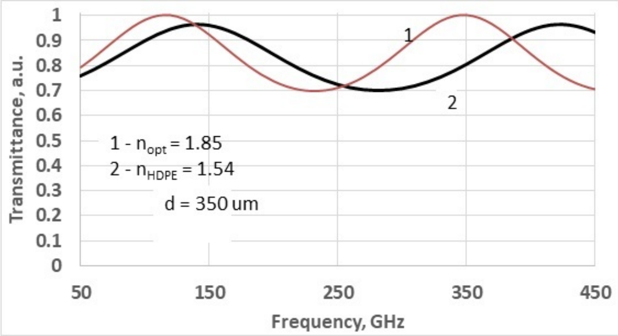

Fig. 3. The estimated dependences of the transmission coefficient on the radiation frequency for ARC/Si structures with different refractive indexes of coating films for the thickness of layers $d = 350$ µm: for film refractive index $n_{HDPE} = 1.54$ and the layer refractive index $n_{opt} = 1.85$.

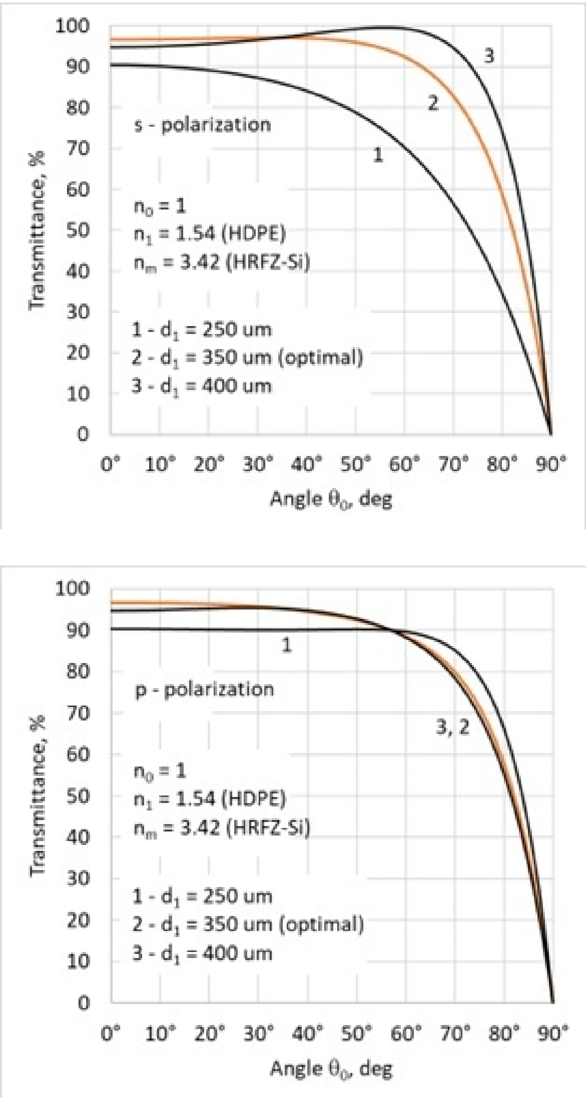

Fig. 4. Calculated dependences of the transmission coefficient on the angle of incidence θ_0 on the HDPE flat surface of the structure HDPE/Si for different thicknesses of HDPE coating films.

The estimations of the shift of radiation frequency, at which the maximum transmission coefficient can be seen for HDPE layer with the refractive index $n_{HDPE} = 1.54$ is observed when shifting to a higher radiation frequency $\nu \approx 0.14$ THz (Fig. 3).

For estimations of transmission coefficients of Si lenses with changing the angles of the falling radiation to the first flat surface of the lens in dependence of distance from their centers using Eq (3), there were calculated the dependences of the transmission coefficients for different HDPE coating thicknesses (Fig. 4). For different radiation polarizations, there were taken the thicknesses of HDPE d_{HDPE} = 250, 350 and 400 µm. It was shown that for *p*-polarization, the changes in the thickness of coatings are less notable for transmission coefficient compared to transmittance for *s*-polarization radiation. For the optimal thickness $d_{HDPE} = 350$ µm at $\nu = 0.14$ THz, the HDPE transmission coefficient weakly depends on the angle of radiation incidence θ_0 at $\theta_0 \leq 50°$. For a lens design were chosen the Si lenses with the following parameters: the diameter of 8 mm and the radius of 12 mm, and the thicknesses not exceeding the value of d = 3 mm. For the system designed, the angles of incidence for radiation were taken to be less than 50°. At these angles of the radiation falling down onto Si lenses, there should not be visible changes in the transmission coefficients for radiation that is incident onto different parts of Si lenses with HDPE coatings of optimal or larger thicknesses (Fig. 4).

3. Technological process

Unlike coatings for visible and near-infrared ranges, where the AR layers are obtained through evaporation or sputtering thin dielectric films, the ARC thicknesses are large for the low THz range and the evaporation procedure of dielectric films is a bit complicated. Other processes allow the fabrication of relatively thick films with an affordable thickness close to the desired quarter wavelength in the material (several tens and hundreds of micrometers). The ARC material must comply with the requirements in the refractive index and be sufficiently flexible and plastic to circum flex the curved surfaces.

In our case for coatings of Si wafers and lenses, we use HDPE layers of hundreds of micrometers in thickness and thin glue layers of ten or less micrometers. The similarity in the refractive indexes of the glue layer and HDPE one produces minor changes in the design or modeling. The HDPE and glue melting points are much lower ($T_{HDPE} \geq 130$ °C, $T_{glue} \approx 100$ °C) as compared to that one of HRFZ-Si (T = 1414 °C) allowing to heat the assembly and melt only the glue and cover layers. Then the mechanical pressure is used to press the HDPE coating and glue layers onto the lens substrate, as it is shown in Fig. 5.

The designed and fabricated chamber enables the coating of the lenses of the needed diameter and thickness. The HDPE coating and glue layers are slowly spread out over the lens or plate substrates (glue-side down), as shown in Fig. 5.

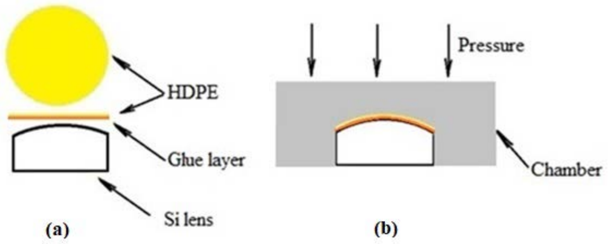

Fig. 5. Schematic of silicon lens, HDPE coating and glue layers (a) and the designed chamber with the formed structure (b).

By this technology, the HDPE layers were obtained on the HRFZ-Si surfaces of thickness *d* within 250…400 µm. The precision molding used here allows for receiving HDPE layers less than ≤50 µm and extends the area of their application in the higher range of THz radiation frequencies. Using technology of pressure molding for obtaining the HDPE interference films reduces the final cost of the THz optical elements as compared to other coatings and methods of their formation.

4. Testing and analysis

In the earlier research [22, 23], there was developed the THz imaging system with sources based on IMPATT diodes with a conical horn antenna with the parameters: the frequency range within $\nu \approx 110…170$ GHz, the gain was ≥ 20 dBi, the waveguide type was rectangular, the waveguide size was WR-6 and the horn length – 38 mm.

For the optical part of the system (Fig. 6), to replace horn antennas there were designed and fabricated 3-mm thick silicon lenses with the radius 12 mm. The refractive index of interference coating layers $n_{HDPE} = 1.54$ [1, 24]. High-resistance ($\rho > 20\,000\ \Omega\cdot$cm), single-crystal silicon was chosen as the lens material, because its properties are well-known at THz frequencies [21].

The radiation distribution after a waveguide without a horn antenna, with a horn antenna, and with a silicon lens was measured using the worked out facility (see Fig. 7). This facility includes the 0.14 THz IMPATT

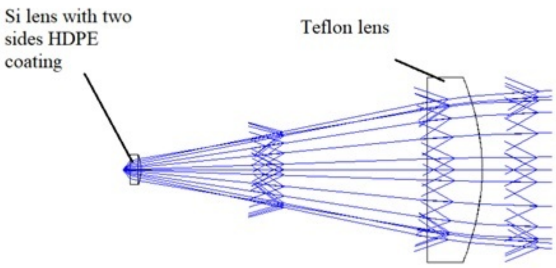

Fig. 6. The optical scheme with the silicon lens that provides illumination of the Teflon lens. The silicon lens has HDPE layers on the both sides, the technology of which was presented above.

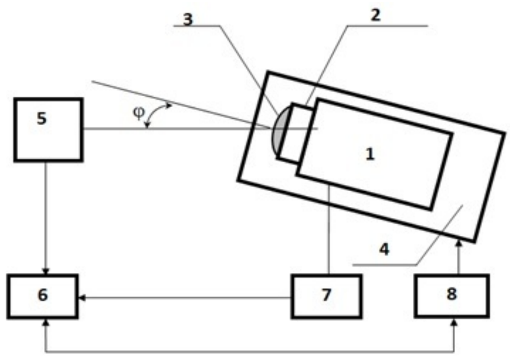

Fig. 7. Schematic setup to study radiation patterns: *1* – 0.14 THz generator, *2* – electric modulator, *3* – lens (or the horn antenna), *4* – rotary platform, *5* – pyroelectric detector, *6* – lock-in amplifier SR-830, *7* – generator of signal modulation (Agilent 33250A), *8* – PC.

diode (*1*) with the electric modulator (*2*), and the clamp for a lens or horn antenna (*3*) under this study, which were located on a rotary platform (*4*). This platform allows changing the angle in the plane between the lens or the horn antenna (*3*) and the receiver (detector) (*5*). The signal levels are controlled by the lock-in amplifier SR-830. The platform (*4*) is moving by a stepper motor and is controlled by PC (personal computer) (*8*). The generator (*7*) generates control signals to a modulator (*2*) and the lock in amplifier (*6*). The radiation passes through the lens or horn antenna (*3*) and is detected by a detector (*5*).

The results of measurements of radiation patterns are presented in Fig. 8.

The radiation pattern in the *E* plane after the wave-guide shows a broadband shape. With a horn antenna, the width of the radiation band pattern at the 0.1 level is about 24 degrees (see Fig. 8). Using the AR silicon lenses,

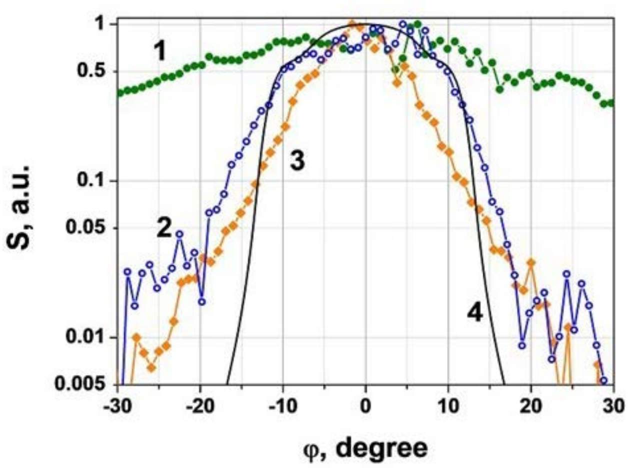

Fig. 8. Measured radiation patterns in *E* plane: *1* is related to the waveguide only, *2* – pattern measured with a silicon lens, *3* – pattern measured with a horn antenna, *4* – pattern calculated for a silicon lens.

Table. Power measurements and the calculated transmission coefficient T for the silicon wafers and lenses with HDPE coatings.

Sample	P, after waveguide, mW	Transmission coefficient, T	Ratios*	Notes
Wafers				
	6.83	1		Input power
1	3.41	≈ 0.5		Wafers (no ARC)
2	4.46	0.65	1.3	Wafers (both sides 350 μm HDPE)
3	4.88	0.71	1.42	Wafers (both sides 300 μm HDPE)
Lenses				
	6.12	1		Input power
4	2.34	0.34		Lens 1 (no ARC)
5	2.39	0.35		Lens 2 (no ARC)
6	3.02	0.47	1.38	Lens 1 (both sides HDPE with d = 325 ± 5 μm)
7	3.28	0.51	1.46	Lens 2 (both sides HDPE with d = 325 ± 5 μm)

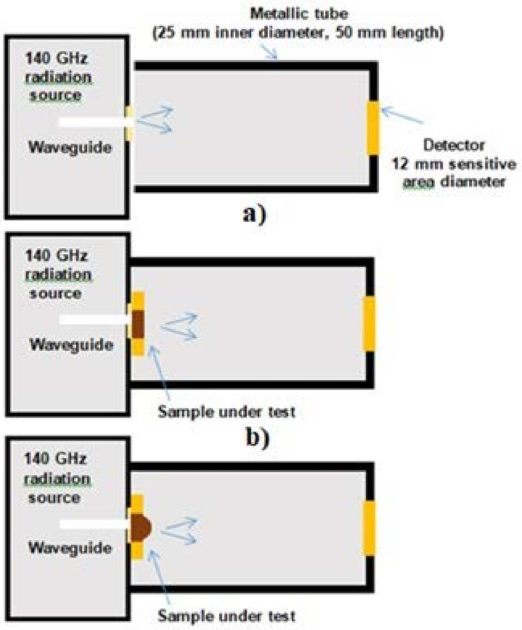

Fig. 9. Power level measurements at the radiation frequency 0.14 THz: a) measurements of the source power after the waveguide WR6, b) transmitted radiation power passed through the silicon wafers, c) transmitted radiation power passed through the silicon lenses.

the radiation band pattern becomes wider and at the 0.1 level is about 31 degrees. Calculation of radiation pattern after the silicon lens, in the optical program ZEMAX, gives a width of the band pattern at the 0.1 level of 26 degrees, which is close to that of horn antenna, but experimental measurements gave the bandwidth equal approximately 31 degrees.

For an analysis of transmission coefficient for HDPE/Si structures, there were additionally fabricated Si wafers of 8-mm-diameter, which were polished to a thickness of 3 mm. Then these wafers were coated with HDPE films.

From Eq. (1), the thickness of the HDPE coating layer (n_{HDPE} = 1.54) for radiation frequency 0.14 THz and maximum transparency level is $t_{HDPE} \approx 348$ μm at normal incidence. For transmission measurements of Si lenses and wafers with HDPE coating layers, we used the scheme shown in Fig. 9. Shown at the top (Fig. 9a) is the schematic for measurement of the radiation power from the 0.14 THz impact avalanche transit-time (IMPATT) diode source. Fig. 9b and Fig. 9c schematically show the results of measuring the radiation power that has passed through the wafers and lenses without and with HDPE coating. In the metallic tube, the radiation power level was measured using the Gentec THZ-12D receiver.

The transmission coefficient of the silicon plates (wafers) or lenses T was estimated by the following ratio:

$$T = P/P_0, \quad (8)$$

where P is the ratio of transmitted radiation power of the Si wafer, with parallel surfaces or lens, and P_0 is the source power after the waveguide.

To select the optimal thickness, there were fabricated HDPE coatings with different thicknesses of $d \approx$ 350, 300 and 250 μm. Here, for data collecting we used the optimal HDPE thickness d = 350 μm, considering the dependence of the transmission coefficient on the angle of incidence on the first flat surface.

Table shows the results of measuring the transmission coefficient T for silicon wafers and lenses with and without HDPE coating layers at the radiation frequency of 0.14 THz. Table also shows that the use of

HDPE coatings provides an increase in radiation transparency for HRFZ-Si wafers and lenses up to approximately 1.45 times at the radiation frequency of 0.14 THz.

During the manufacturing process, HDPE films were obtained with the thickness another than the optimal one. Changes in the thickness of HDPE films as compared to the optimal thickness do not lead drastically to the changes of the transmission coefficients in the low frequency part of the THz range. These variations can only slightly affect the frequency of the best ARC match, but the overall performance of wafers and lenses with ARC is not significantly affected.

5. Conclusions

The increase of the transmission coefficients of the high resistance floating-zone silicon (HRFZ-Si) wafers and lenses for the THz range, which were covered by HDPE interference films obtained by their precision press molding, has been shown. The optimal thickness of $d \approx 350$ μm and the angles of the radiation incidence at $\nu = 0.14$ THz to the Si surfaces ≤50° increase the transparency coefficient up to 1.45 times. Application of the HRFZ-Si/HDPE structures in the THz imaging or communication technologies is feasible to be used. The precision molding allows getting HDPE layers in a wide range: 50 μm $\geq d \geq$ 400 μm, which essentially extends the domain of their applications. Usage of technology for pressure molding to obtain the HDPE interference films for the THz range reduces the cost of the THz optical elements as compared to other coatings and the methods of their formation.

Acknowledgement

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Лінзи з високооомного кремнію з просвітлюючим покриттям з поліетилену високої щільності для низькочастотного терагерцового діапазону частот

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Анотація. Представлено моделювання, виготовлення та тестування оптики з високооомного кремнію (HRFZ-Si) з просвітлюючим покриттям з поліетилену високої щільності (ПВЩ) для низькочастотного терагерцового діапазону частот (ν ≈ 0.14 ТГц), з використанням технології пресування. Експериментальні результати пропускання кремнієвих пластин та лінз з двостороннім ПВЩ покриттям для частоти випромінювання 0,14 ТГц показали збільшення значень пропускання *T* у ≈1.45 раза порівняно з величинами *T* у пластинах та лінзах без просвітлюючого покриття. Показано можливість використання лінз з ПВЩ покриттям за технологією прямого пресування як економічна альтернатива застосуванню ріжкової антени для 0,14 ТГц. Зважаючи на активний розвиток THz візуалізації та 6G комунікаційних технологій є перспективним подальша реалізація такого типу оптичних елементів з покриттям із ПВЩ.

Ключові слова: лінзи з високооомного кремнію, просвітлююче покриття з поліетилену високої щільності (ПВЩ), ТГц.