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Determination of thickness and doping features of multilayer $4H$-SiC structures by frequency analysis of IR reflection spectra

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A technique has been developed for frequency analysis of the IR reflection spectrum to determine the thickness and order of the layers in the epitaxial structure of silicon carbide. Calculations for the $4H$-SiC epitaxial structure have been performed. The method has been shown to be highly sensitive to optical boundaries resulting from a sequential increase in the doping level during the layer growth.

Keywords: Silicon carbide, epitaxial layer, IR reflection, spectrum

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A unique combination of electrophysical properties of the $4H$ silicon carbide polytype ($4H$-SiC) enables creating based on it power electronics devices that are vastly superior to their silicon–based analogs with respect to such most important parameters as the active region resistance, switching loss, switching power density, operating temperature and frequency. Therefore, development of the silicon–carbide electronics component base causes application of innovative efficient and fast methods for analyzing epitaxial device structures (ESs), including controlling the layer thicknesses that essentially affect the device characteristics [1,2].

When electromagnetic waves are being incident on a plane–parallel sample, a part of the irradiation reflects from the air–top layer interface, another part penetrates into ES where undergoes a series of reflections and refractions at interlayer interfaces. Waves that refract at the top layer–air interface and move backward interfere with waves reflected from the structure top boundary. The wavelength dependence of the interference amplitude detected by a photoreceiver has the periodic character and is the spectral interference. The path difference of interfering waves is defined by the distance between the structure surface and boundary wherefrom the wave has been reflected. This is why the reflection spectrum contains components corresponding to top layer thickness d_n, cumulative thickness of the top layer and next layers $d_n + d_{n-1}$, etc. Experimental reflection spectra measured on two $4H$-SiC ESs are presented in Fig. 1, the corresponding process characteristics of the layers, as well as measurements obtained in this work, are listed in the table. In the constant refractive index approximation ($n \approx 2.64$ [3]), it is possible to relate to each spectral component a layer thickness calculated as $d = (2\omega' n)^{-1}$ [4] where ω' is the period of interference spectral oscillations. Visual estimation of periods of spectrum oscillations (especially of low–frequency „beats“) that are superposition of sinusoids can hardly be performed since it can give identical results for different combinations of initial periods. Hence, frequency Fourier analysis of the reflection spectrum is necessary.

To correctly determine the epitaxial layer thicknesses, the reflection spectrum range is used where the material, i. e., silicon carbide, has no absorption lines, and its refractive index possesses low normal dispersion. Therefore, to characterize multilayer SiC ESs it is necessary to: 1) exclude from the spectrum used for the frequency analysis the range of single–photon (near $1000\,\mathrm{cm}^{-1}$) and plasmon (below $1000\,\mathrm{cm}^{-1}$) resonances [5,6]; 2) eliminate from the processed experimental spectral curve the trend line arising due to the existing low dispersion of the refractive index.

The result of revealing in the Fourier transform spectrum the harmonic we are interested in depends on whether the number of its periods that are able to be accommodated in the analyzed region is integer or not. If this number is not integer, then the Fourier transform spectrum contains peaks at the frequencies that do not relate to the real superimposed harmonics but are near the real ones; simultaneously, a

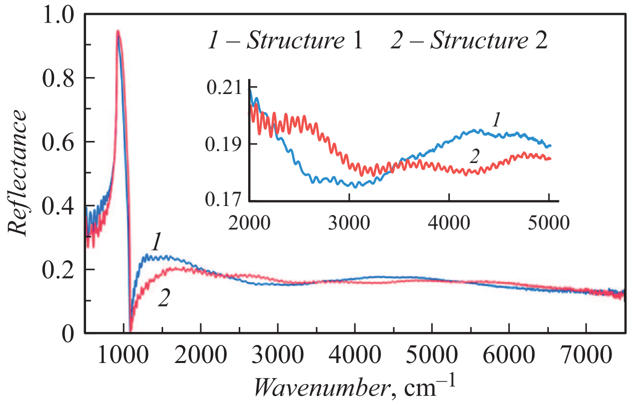

Figure 1. Experimental reflection spectra. The inset presents the zoomed section.

The ES 1 and 2 nominal data and results of the reflection spectra Fourier analysis

Number of the structure	Parameter		Parameters of epitaxial layers (numbered from the substrate)				
			1	2	3		
1	Techical certificate	Type of conductivity Doping concentration, cm^{-3} Thickness, μm	n^+ $5\cdot10^{18}$ 10	p $1\cdot10^{16}$ 16	p^+ $5\cdot10^{18}\to1\cdot10^{20}$ 5		
	Thickness by spectrum (Fig. 2, *a*), μm		9.25	16.4	2.05	2.05	1.03
2	Technical certificate	Type of conductivity Doping concentration, cm^{-3} Thickness, μm	n^+ $5\cdot10^{18}$ 10	p $1\cdot10^{16}$ 16	p^+ $5\cdot10^{18}\to1\cdot10^{20}$ 2.5		
	Thickness by spectrum (Fig. 2, *b*), μm		12.7	15.5	1.11	1.11	0.553
	Thickness by spectrum (Fig. 2, *c*), μm		12.8	15.6	1.11	1.11	0.556

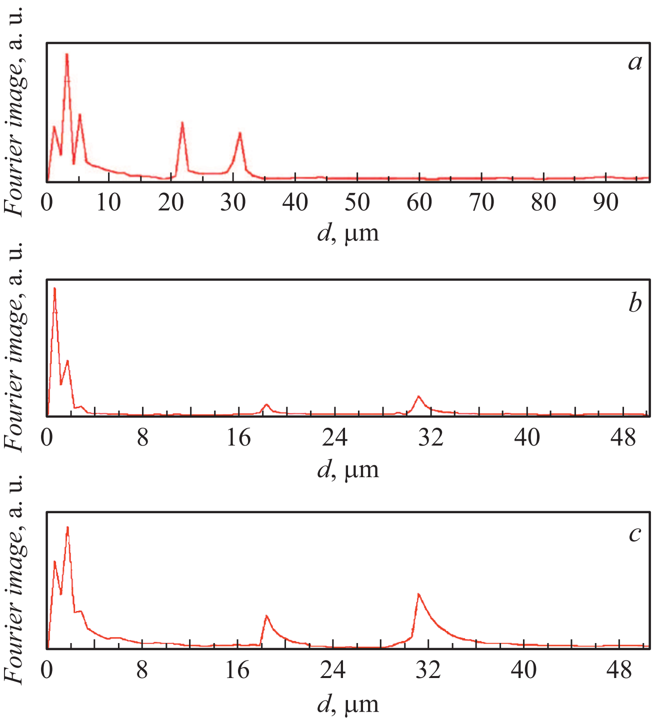

Figure 2. Results of the reflection spectra Fourier analysis. *a* —structure 1; *b* — structure 2, range 2370−5783 cm^{-1}; *c* — structure 2, range 1843−5240 cm^{-1}.

decrease in the real peak amplitudes takes place. Thus, in order to minimize the number of „side" peaks appearing in the Fourier transform spectrum, as well as to reveal and increase the amplitudes of „true" peaks, the analyzed range will be corrected so as to make it possible to use in the Fourier transform an integer number of periods of the harmonic part under consideration.

Fig. 2 presents the results of Fourier analysis of the studied structures calibrated in layer thicknesses. Keep in mind that the first peak indicates the top layer thickness, the second one indicates the cumulative thickness of the top layer and layer beneath it, and further in the same order. The minimal thickness determinable according to the spectrum ranges is about 0.5 μm.

The algorithm used in this work for analyzing the silicon−carbide ES reflection spectrum is quite sensitive. For instance, it allowed detection of existence of optical boundaries in the structure of a high voltage mesa−epitaxial 4*H*-SiC *p*−*i*−*n*-diode in which a highly doped p^+-emitter was created on the *p*-layer with relatively low concentration of non−compensated acceptors (N_A-$N_D = 5\cdot10^{15}$ cm^{-3}) [7]. The high, almost limiting for Al in SiC doping level was reached step−by−step during the epitaxial growth according to the earlier developed procedure [8]. Fig. 3 presents a SEM image of the emitter region typical for such device structures; the image contrast indicates the existence of sublayers with different concentrations of an acceptor impurity. Fig. 2 shows the peaks in the spectrum Fourier images corresponding to the sublayer thicknesses; the Table presents numerical values

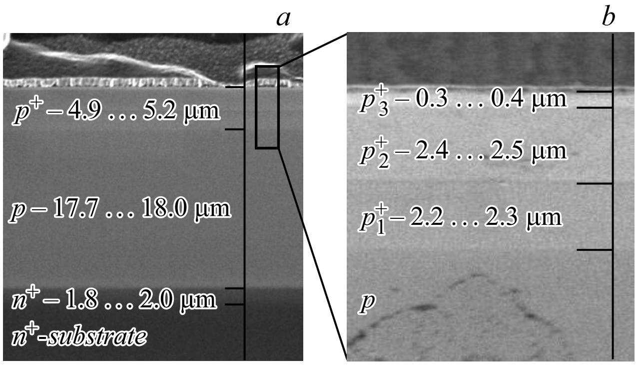

Figure 3. SEM image of a silicon−carbide ES in the doping contrast mode. *a* — the ES layer−by−layer composition, *b* — the p^+-emitter composition.

of sublayer thicknesses determined in this work by the noncontact method.

Thus, the paper represents a noncontact technique for determining layer thicknesses in the 4*H*-polytype silicon—carbide device structures; the technique is quite sensitive to the optical boundaries both between the specially created functional regions and between the layers formed as a result of controlling the deposition process. Using the frequency analysis of reflection spectra in the near— and far—IR ranges, we have simultaneously determined thicknesses of five epitaxial layers, which means that it is possible to apply the developed technique in nondestructive analysis of multilayer 4*H*-SiC ESs.

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Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] S. Oishi, Y. Hijikata, H. Yaguchi, S. Yoshida, Jpn. Soc. Appl. Phys., **45** (46), L1226 (2006). DOI: 10.1143/JJAP.45.L1226

[2] Z.-Y. Li, J.-W. Sun, Y.-M. Zhang, Y.-M. Zhang, X.-Y. Tang, Chin. Phys. Lett., **27** (6), 068103 (2010). DOI: 10.1088/0256-307X/27/6/068103

[3] *Handbook of optical constants of solids*, ed. by E.D. Palik (Academic, San Diego, 1998).

[4] V.V. Batavin, Yu.A. Kontsevoy, Yu.V. Fedorovich, *Izmerenie parametrov poluprovodnikovykh materialov i struktur* (Radio i Svyaz', M., 1985) (in Russian).

[5] K. Narita, Y. Hijikata, H. Yaguchi, S. Yoshida, S. Nakashima, Jpn. J. Appl. Phys. A, **43** (8), 5151 (2004). DOI: 10.1143/JJAP.43.5151

[6] M.F. Panov, F.E. Rybka, V.P. Rastegaev, v sb. *V Mezhdisstsiplinarny nauchny forum „Novye materialy i perspektivnye tekhnologii*“ (M., 2019), t. 1, s. 377 (in Russian).

[7] A.V. Afanasjev, V.A. Golubkov, V.A. Ilyin, V.V. Luchinin, A.A. Ryabko, K.A. Sergushichev, V.V. Trushliakova, S.A. Reshanov, Izv. LETI, № 6, 72 (in Russian) (2020).

[8] A.V. Afanasjev, V.A. Ilyin, V.V. Luchinin, S.A. Reshanov, Izv. Vuzov. Elektronika, **25** (6), 483 (2020) (in Russian). DOI: 10.24151/1561-5405-2020-25-6-483-496