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4H-SiC P-i-N Diodes: Development of Technology and Research of Microwave Switches Based on it

A.A. Lebedev[1,2], A.V. Kirillov[3], L.P. Romanov[3], A.V.Zubov[4], A.M. Strelchuk[1].

[1]Ioffe Institute., 194021, St. Petersburg, Polytechnical street 26, Russia

[2] St. Petersburg State Electrotechnical University LETI named after V.I. Ulianov (Lenin), St. Petersburg, 197376

[3]CJSC "Svetlana-Electronpribor", St. Petersburg 194156, Engels Prospect, 27, Russia

[4]National Research University of Information Technologies, Mechanics, and Optics, St. Petersburg 197101, Russia

Abstract: ***The technology of microwave p-i-n diodes based on silicon carbide (SiC) has been developed. Using this diodes manufactured switches for 3-cm range. It is shown that the developed devices have an operating power of about 10 times the operating power of switches based on Si diodes with an equal base thickness of 5 microns. Outlined ways to further optimize the technology of these devices.***

1. Introduction

Due to the large band gap, high thermal, chemical and radiation resistance of SiC is a promising material for the creation of semiconductor devices [1-6]. Earlier, we demonstrated the possibility of creating a switch based on 4H-SiC p-i-n diodes in the frequency range of ~ 10 GHz.

The purpose of this work was the development of manufacturing technology and design of SiC p-i-n diodes for devices of the microwave range: switches, modulators, attenuators and phase shifters.

4H-SiC p-i-n diodes were fabricated based on the 4H-SiC epitaxial structure, manufactured by CREE (USA) [7] and Ascatron (Sweden) [8]. These structures were n + substrate with a concentration of donors (Nd-Na) ~ 1-2 • 10^{19} cm^{-3}, 360 µm thick with two successively grown epitaxial layers: n- (Nd-Na ~ 0.4-2 • 1015 cm -3, 7-15 microns thick) and p + (Na - Nd ~ 10^{19} cm^{-3}, ~ 1 microns thick)

2. Technology

To reduce the resistance of the diode, the substrate was thinned by grinding to a thickness of ~ 120-130 microns. Before the formation of mesa structures on the surface of the epitaxial layers, aluminum masks 40–200 µm in diameter were created using explosive photolithography. Mesa structures with a height of ~ 2 µm were formed by plasma-chemical etching in an SF6 + 02 plasma using a Plasmalab-100 installation.

The selected etching mode (0.5 nm / min) provided a smooth surface, and the angle of inclination of the mesa was 72-75 ° to the crystal surface. Then the surface of the mesa structure was oxidized at 1100 ° C in a humid oxygen atmosphere for 120 minutes, during which a protective oxide film was formed with a thickness of about 10 nm. Before sputtering, the oxide film was removed, ensuring surface cleaning.

To create ohmic contacts to the p + - layer, layers of metal, Al / Ti / Ni 50/50/200 nm thick, were sprayed onto its surface. Contacts to the n + - substrate were obtained by sputtering a metallization, Ti / Ni / 40/250 nm thick. The deposition of metals was carried out on the installation of electron-beam deposition. Further, the annealing procedure was carried out at a temperature of 1050 ° C for 60 sec in a high vacuum.

In this case, low-resistance ohmic contacts were formed with contact resistance of 6–7 • 10^{-6} ohm • cm^2 (p + - type) and 1 • 10^{-4} cm^2 (n + - type). The diameters of the formed contacts were 10 µm smaller than the diameter of the mesa structure. For the subsequent soldering, the metallization was enhanced by Ti / Au sputtering on both sides with the subsequent galvanic deposition of gold ~ 2-3 µm.

The structure of the diode chip obtained is shown in Fig. 1 and a general view of the structure in Fig. 2

After cutting the plate into individual chips, about 1 mm^2 in size, rejection was performed on the reverse breakdown voltage. Then the chips were soldered with gold-tin solder into standard metal-ceramic cases KD-110. The output from the p + contact was carried out by thermal compression of a gold wire with a diameter of 30 µm. The design of the case diode is shown in Fig.3

3. Experimental Results and Discussion

Measurements of the breakdown voltages of the obtained diodes showed that the leakage at the level of 10 Å began at a voltage of 600 V, regardless of the base thickness (7–15 mm). Some structures had a breakdown voltage of ≥ 1000 V. A detailed study of the causes of breakdown showed that leaks occur along the lateral surface of the mesa structure. Initially, sparking was observed on the surface, then irreversible breakdown developed.

Further improvement in the characteristics of the device can apparently be achieved by reducing the electric field strength on the surface of the semiconductor. For example, by creating compensated near-surface areas and covering the surface of the diode structure with an organosilicon silicon compound GKN

The differential resistance Rd (Fig. 4) of the enclosed structures (at currents of 5–10 mA) was about 10 Ω. At currents of 100 mA, the resistance of the diodes was reduced to 1 - 1.5 Ohms, which is quite acceptable for operation in microwave devices.

Measurement of the current-voltage characteristics of the packed p-i-n diodes in the temperature range was carried out. The case diode was heated in the atmosphere on a heated base (table). Controlled the temperature of the table (thermocouple). Contacts to the case were clamping. The temperature behavior of the IVC diode with forward and reverse bias is shown in Fig. 5.

The behavior of reverse current is typical enough for 4H-SiC p-i-n structures. In particular, the parameter Jo of the generation – recombination current in 4H-SiC pin structures is ~ 10^{-4} A / cm^2 at 900 K, which is close enough to the experimentally observed reverse current ~ 10^{-6} A) at the highest temperature (which was about 600 ° C) (Fig.5b).
High-frequency studies and high-level microwave power tests were carried out on two types of switches based on a waveguide-slit line using unpackaged SiC p-i-n diodes and based on a waveguide-pin switch design using enclosed SiC p-i-n diodes.

Figure 6 shows the frequency characteristics of the losses of locking and transmission of switches on a waveguide-slit line, assembled on the basis of SiC p-i-n diodes with a different structure diameter and the same thickness of the n + substrate 360 μm.

From the presented data it follows that with an increase in the substrate diameter, the value of the introduced attenuation increases by 4 dB while simultaneously increasing the transmission loss by 1.5 dB. In this case, an increase in transmission loss is associated with an increase in the size of the structure capacitance.

In fig. 7 shows similar characteristics of switches on SiC p-i-n diodes with a diameter of 80 μm, differing in substrate thickness - 360 and 160 μm, respectively.

From the presented data, it follows that with a decrease in the thickness of the n + - substrate, the gain in the attenuation introduced is 4 dB, i.e. as much as increasing the diameter of the structure from 80 to 150 microns. At the same time, this gain is achieved without an increase in transmission loss, in contrast to the case of an increase in the diameter of the structure.

Tests of developed SiC p-i-n microwave diodes at a high power level showed the ability to withstand pulsed power up to 2.4 kW in the locking mode and up to 1 kW in the transmission mode. The main character of failures is the surface breakdown of the pn junction, which indicates that the breakdown voltage of SiC p – i – n diodes is not high enough.

4. Conclusion

Based on the results of a sample of switches based on SiC p-i-n diodes, the following conclusions can be made

1) Experimentally shown the possibility of implementing on the basis of SiC p-i-n diodes the following characteristics of switches in the 3-cm range:
   a) locking losses - 22 ... 25 dB;- loss of transmission - 0.7 ... 1.0 dB;
   b) operating pulse power in the locking mode - 1.6 ... 2.4 kW.
2) The obtained switches are approximately 10 times larger than the operating power of switches based on Si diodes with an equal base thickness of 5 microns.
3) It is shown that reducing the thickness of the n + substrate from 360 μm to 160 μm allows increasing switch locking by 4 dB, which leads to a decrease in the power dissipated in the diode and, consequently, an increase in the operating power of the switch.
4) To increase the operating power of the switch in the transmission mode, it is necessary to significantly increase the breakdown voltage of SiC p-i-n diodes to a value of 1000 V or more.
5) By reducing the substrate thickness to 100 ... 120 μm with the thickness of the n + layer 8 ... 10 μm and increasing the magnitude of the reverse voltage to 1500 V, switches with an operating pulse power up to 4 ... 5 kW can be realized.

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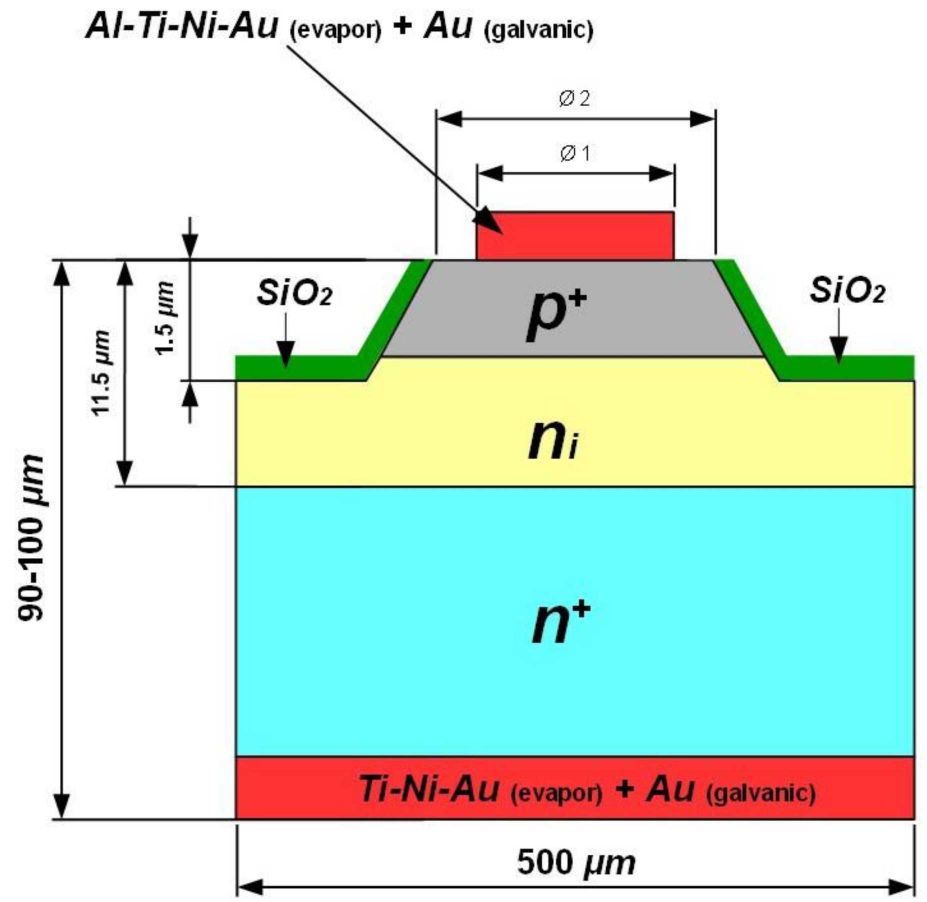


Figure 1: General view of the obtained 4H-SiC p-i-n diode. For all sizes of mesa structures, the diameter of the ohmic contact (Ø1) was 10 µm smaller than the diameter of the mesa (Ø2).

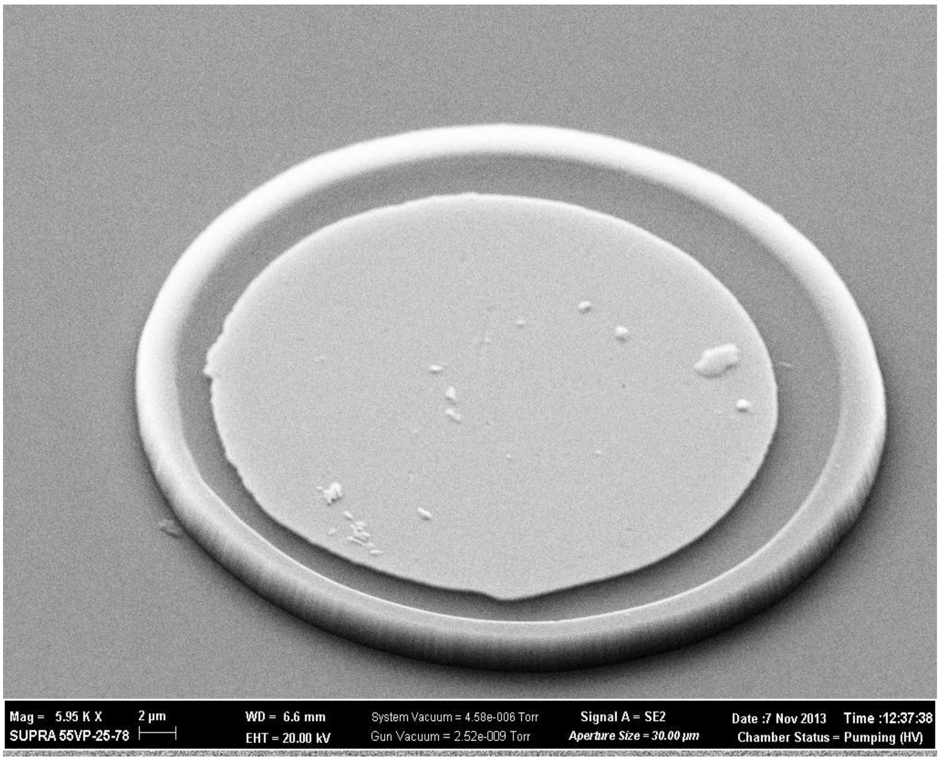


Figure 2: Appearance of the p-i-n diode structure

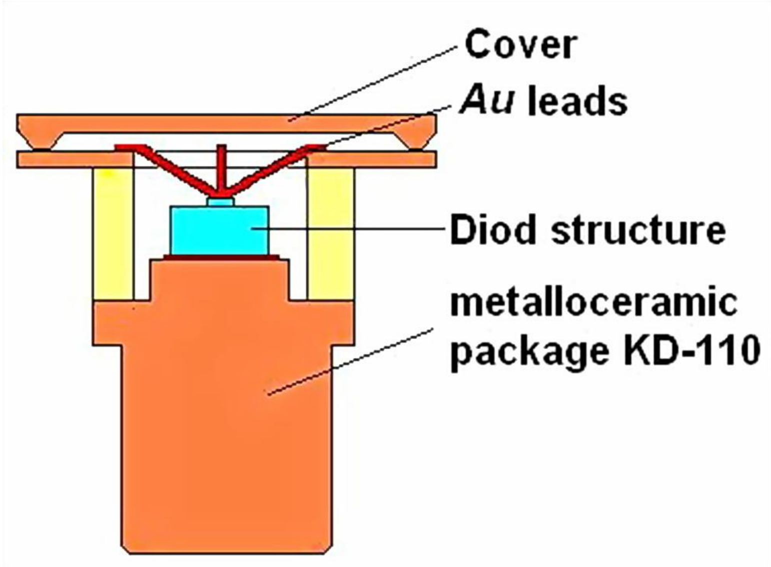


Figure 3: Bundled SiC p-i-n diode

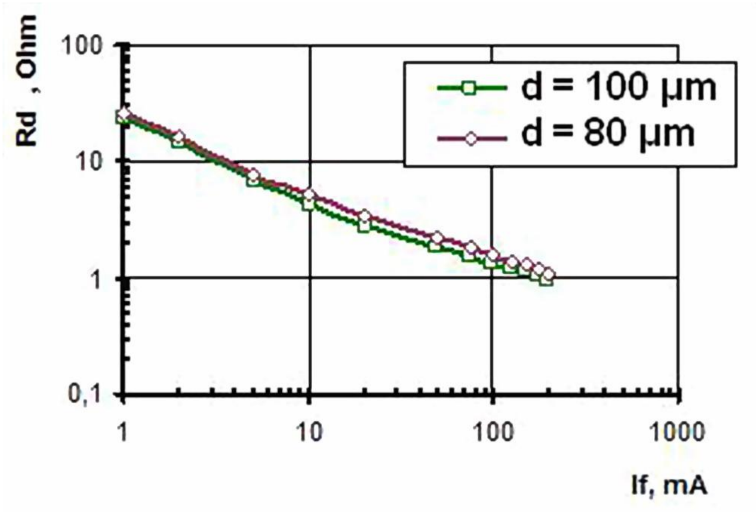
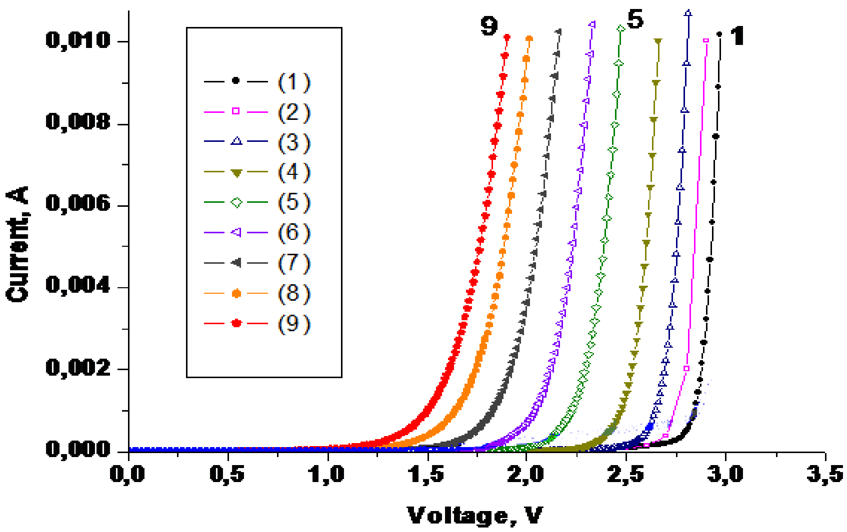
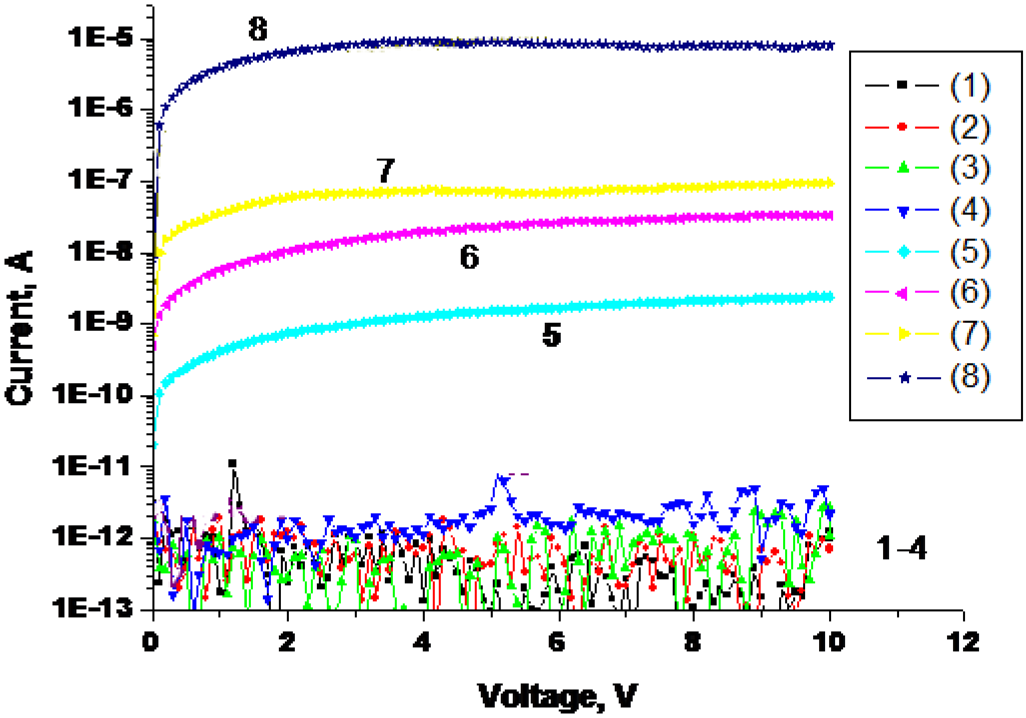


Figure 4: The dependence of the differential resistance of SiC p-i-n diodes from the direct current.



(a)



(b)

Figure 5: Direct (a) and reverse (b) IVC of a 4H-SiC p-i-n-enclosed structure when heated from 23 ° C (curves 1) to 600 ° C (curves 9)

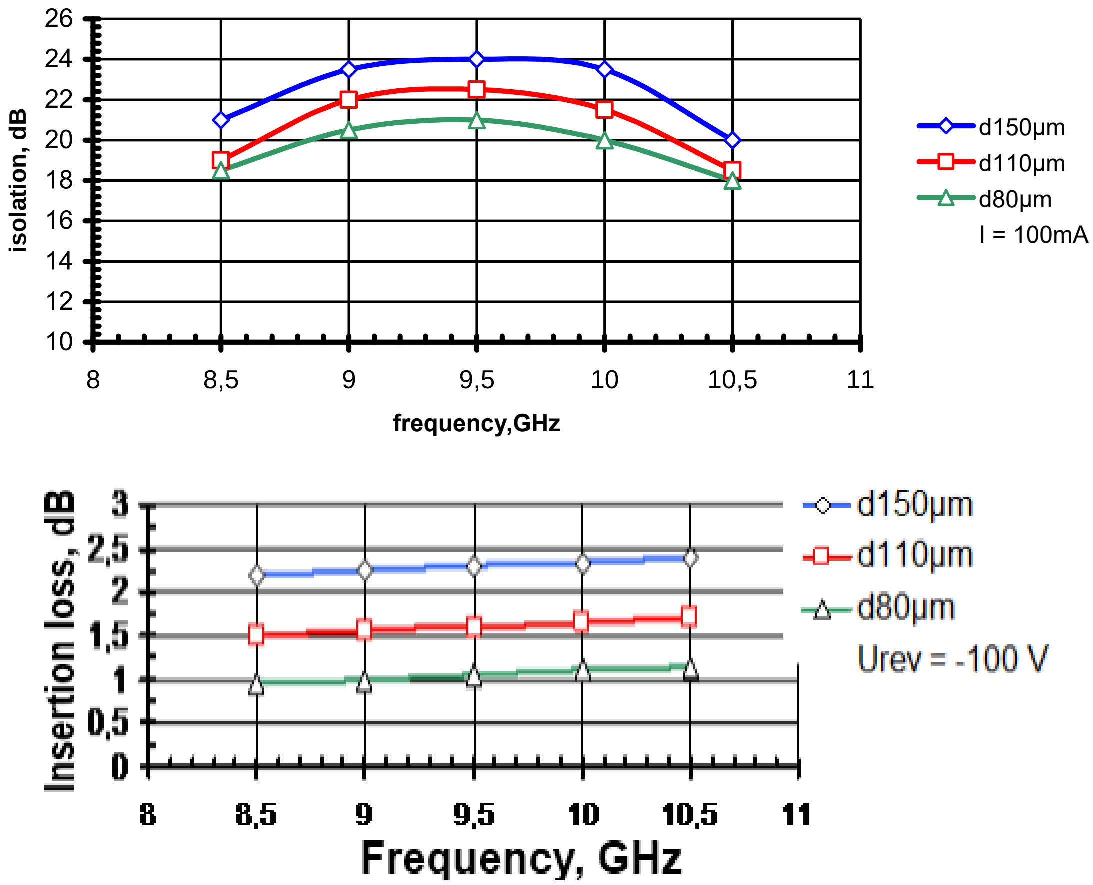


Figure 6: Frequency characteristics of losses of locking and transmission of switches on a waveguide-slot line

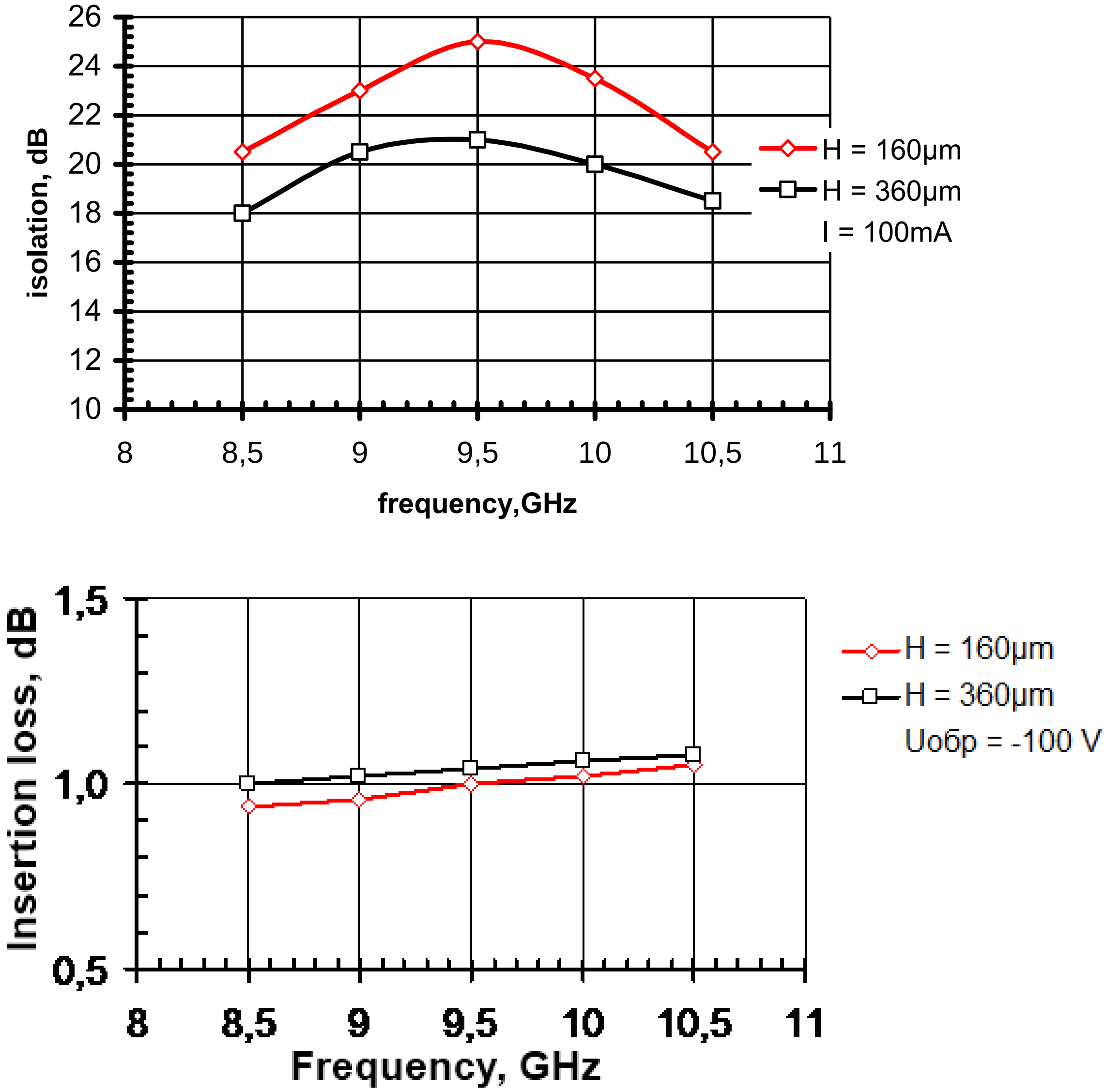


Figure 7: Frequency characteristics of losses of locking and transmission of switches on SiC p-i-n diodes with different thickness of n + - substrate - 360 and 160 μm, respectively.