Temperature dependence of silicon carbide drift step recovery diodes injection electroluminescence

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Abstract. The experimental results of silicon carbide (SiC) drift step recovery diodes (DSRDs) temperature dependence of injection electroluminescence (IEL) spectra were presented. It was shown that in the forward current range \( I_f = 0,1 \ldots 1 \) A the DSRD-dies temperature was raised from 327 K to 546 K correspondingly. While the short-wavelength maximum of IEL spectra - \( \lambda_{\text{max}}1 \) shifts from 392.4 to 402.1 nm and possesses dependence close to linear. On the basis of obtained calibration curves it is possible the non-contact temperature measuring of SiC-DSRDs by electroluminescence spectra at their operation in the generator of high voltage pulses.

1. Introduction
Among the diode opening switches which are used in the voltage pulse generators with the inductive energy storage, the drift step recovery diodes (DSRDs) occupy particular place [1]. In [2,3] are presented the results of development of the voltage pulse generators with use of silicon carbide DSRDs which form the voltage impulses of nano- and subnanosecond duration with a peak power of hundreds of kilowatt up to megawatt units and pulse repetition rate of tens to hundreds of kHz in continuous operation. For designing of the optimal structure of 4H-SiC-DSRDs, evaluating of the effectiveness of the cooling system and to prevent the overheating and selection of the optimal functioning mode of SiC switches at their operation as a part of the voltage pulse generator it is necessary to have accurate information on the device temperature. The application of optical temperature control methods allows measuring the DSRD temperature in operation mode of high-voltage pulse generator. In this case, the additional temperature sensors are not necessary in generator scheme.

The aim of this work is the experimental determination of the temperature dependence of the injection electroluminescence (IEL) spectra of 4H-SiC-DSRDs at various values of direct forward currents.

2. Experimental Details
4H-SiC DSRD samples were fabricated on 4° off \( n \)-type 4H-SiC wafers with \( p^+\)-\( p^-n^+ \) CVD grown epitaxial stack. The \( n^+ \)-emitter layer of 3\( \mu \)m with net donor concentration of \( 3 \cdot 10^{18} \text{ cm}^{-3} \) was grown directly on the substrate. The \( p^- \)-drift layer of 15\( \mu \)m with Al concentration is of \( 5 \cdot 10^{19} \text{ cm}^{-3} \). The \( p^+ \)-emitter of 1.5 \( \mu \)m with Al concentration of \( 1 \cdot 10^{19} \text{ cm}^{-3} \) forms the structure’s top layer. This \( p^-\)-\( p^-n^+ \) stack has been optimized using Synopsys Sentaurus TCAD software for switching time of a DSRD with a maximum reverse voltage of 1800V. Based on the data obtained in the work [4,5] the effects of high doping and high injection levels, cascade generation and incomplete dopants ionization were
accounted in the simulation. DSRD samples were fabricated in form of mesa-diodes with active area 2mm² and die-size 2.5x2.5 mm². Top view of fabricated 4H-SiC-DSRDs is presented in Figure 1.

A direct current has been transmitted through 4H-SiC-DSRDs which value have been changed within the range from 0.1...1 A in increments of 100 mA. Diodes` temperature has been measured by a chromel-alumel thermocouple. Additional control of diodes temperature has been carried out by thermal imaging infrared camera FLIR A315. In preliminary experiments divergence diode`s temperature measurements using thermocouples and an infrared camera does not exceed a few percent. The spectral characteristics of the 4H-SiC-DSRDs IEL have been recorded by compact optical spectrometer ISM3600 developed by St. Petersburg Electrotechnical University [6]. With precision positioner Cascade Microtech DCM210 fiber optic line installed at a distance of 100…200 µm from the end of the test sample 4H-SiC-DSRDs.

3. Experimental Results
The spectral characteristics of 4H-SiC-DSRDs IEL for the respective temperature values are shown in Figure 2. From the presented dependence is seen that at the diode temperature T = 327 K short wavelength (λₘₐₓ₁ = 392.4 nm) and long wavelength (λₘₐₓ₂ = 425.1 nm) maximums are equal by value. With increasing of forward current (and diode temperature respectively), the short wavelength maximum (λₘₐₓ₁ = 392.4 nm) is shifted to longwave. The inset to Figure 2 shows the temperature dependence of the energy position of short wavelength maximum Eₘₐₓ₁ spectral dependences of the electroluminescence DSRDs. A certain tilt of the approximation straight line to the experimental data of the temperature coefficient β of E_{IEL}(T) has a value 3.2·10⁻⁴ eV/K. The resulting value is close to the temperature coefficient of silicon carbide bandgap obtained in [7,8]. Thus, we can say that the change in the maximum spectral characteristics DSRDs electroluminescence associated with the temperature dependence of the band gap of silicon carbide.
Experimental verification of the possibility of non-contact measurement of the silicon carbide DSRDs temperature was carried out at his work as an opening switch in the voltage pulse generator, which scheme is shown in Figure 3. The operating principle of scheme is as follows. From the external clock oscillator enters the rectangular control pulse of duration of 50...100 ns, performing the activation of the switch S1, which acts as a MOSFET-transistor IXZ631DF18N50 (IXYS Corp.), whose maximum pulse current is of 95 A. After opening of the switch S1 through the diode D1 (4H-SiC-DSRD) is passed the direct current pulse which carries out injection of the electron-hole plasma to the diode p-base. At the end of the control pulse from an external clock oscillator, the voltage at the DSRD abruptly changes its polarity, wherein the reverse current flows through the diode D1. When all the nonequilibrium electron-hole plasma is derived from the diode by the reverse current, the diode is changed over to the locked condition and at the Rload is formed fast rising voltage pulse which amplitude and timing parameters are determined both by DSRDs and a scheme in which it operates.

Figure 3 represents the photo of the generator output part which is responsible for operation of silicon carbide DSRDs and formation of high-voltage pulses. In Figure 3 are pointed: 1 – 4H-SiC-DSRD, 2 – the clamping contact to the p⁺-electrode of the diode, 3 – the optical fiber cable.

In Figure 4 is shown the oscillogram of the voltage pulses which are formed by the generator with the developed 4H-SiC-DSRDs as an opening switch. The amplitude of the pulses is equal to 1800 V, the duration at full width at half maximum (FWHM) is of 2.3 ns, the duration of the leading edge is
1050 ps. The pulse repetition frequency can vary from a few to hundreds of kHz in continuous mode and is limited to the maximum operating temperature of the diode.

![Graph](image)

**Figure 4.** The oscillogram of formed pulses by generator with developed 4H-SiC-DSRDs.

For experimental verification of the possibility of non-contact measurement of silicon carbide DSRD temperature at switching of high-voltage pulses was done as follows. Sequentially change the pulse repetition rate of output voltage pulses, which led to an increase in the average switching power, and as a consequence, to the heating of the diode structure. Using measurements of the electroluminescence spectra of 4H-SiC-DSRDs, it was found that an increase in the frequency of the output voltage pulses corresponding to the diode heating occurs.

Described in this paper the non-contact temperature measurement method can be used to determine the temperature not only of individual diodes, but diodes assembled in a high-voltage stack that is capable of switching the value of units-hundreds of kilowatts, and consisting of tens of diodes. Figure 5 shows a high-voltage assembly, consisting of four silicon carbide DSRDs and capable of switching voltage of about 7 kV value.

![Image](image)

**Figure 5.** High-voltage diode assembly, consisting of four 4HiSiC-DSRDs.

### 4. Conclusion

As a result of experimental studies of the temperature dependence of the spectra of the injection electroluminescence developed SiC drift step recovery diodes it was found that by increasing the diode temperature from 327 to 546 K, the maximum $\lambda_{\text{max}}$ of the spectral lines shift ($\lambda_{\text{max}1} = 392.4$ nm, $\lambda_{\text{max}2} = 425.1$ nm) in long-wave part of the spectrum and is associated with the heating of the DSRDs, which
is explained by the temperature dependence of the band gap. Define of the received dependencies the temperature coefficient $\beta$ of $E_{\text{IEL}}(T)$ has a value of $3.2 \cdot 10^{-4}$ eV/K.

On the basis of experimental data on the temperature of silicon carbide diode structure when working with direct current and temperature dependences of the spectrum maximum injection electroluminescence it is possible to determine with high accuracy (a few Kelvin) in a contactless manner the temperature of 4H-SiC-DSRDs at their work in the structure of the high-voltage generator of ultrashort voltage pulses.

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