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Electrical and noise properties of proton irradiated 4H-SiC Schottky diodes

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The current voltage characteristics and the low-frequency noise in high voltage 4H-SiC junction barrier Schottky diodes irradiated with high energy (15 MeV) protons were studied at different temperatures and irradiation doses Φ from $3 \times 10^{12}\,\mathrm{cm}^{-2}$ to $1 \times 10^{14}\,\mathrm{cm}^{-2}$. Irradiation led to the increase of the base resistance and the appearance of slow relaxation processes at small, $V \leq 0.2$ V, and at rather high, $V \geq 2$ V, forward voltages. The characteristic times of these relaxation processes ranged from $\sim 1\,\mu$s to 10^3 s. The exponential part of the current-voltage characteristic was only weakly affected by irradiation. The temperature dependence of the base resistance changed exponentially with temperature with activation energy $E_a \sim 0.6$ eV, indicating that the $Z_{1/2}$ level plays a dominant role in this process. The temperature increase also led to the increase of the ideality factor from 1.05 at 25 °C to 1.1 at 172 °C. At elevated temperatures and high forward voltages $V > 2$–4 V, the current voltage characteristics tend to be super-linear. It is concluded that at high voltages, the space charge limited current of majority carriers (electrons) and hole injection from the *p-n* regions play an important role in the formation of the current voltage characteristic. The frequency dependences of noise spectral density S of proton irradiated Schottky diodes have the unusual form of $S \sim 1/f^{0.5}$. *Published by AIP Publishing.* https://doi.org/10.1063/1.5018043

I. INTRODUCTION

High power SiC Schottky diodes are important components of high speed power electronic systems of motor vehicles, large solar array switches, aviation and space electronics, etc. At present, high power Schottky diodes are always designed as structures where Schottky contacts alternate with the *p-n* regions. These so-called Junction Barrier Schottky (JBS) diodes have an advantage of higher than *p-n* diode speed and lower than regular Schottky diode reverse leakage current (see, for example, Refs. 1–4).

High radiation hardness of semiconductor devices in relation to various types of radiation is a very important parameter for numerous applications. It was found that different types of irradiation differently affect SiC devices. For example, 4H-SiC neutron detectors do not degrade significantly after neutron irradiation with the dose of $1 \times 10^{17}\,\mathrm{cm}^{-2}$.[5] On the other hand, proton irradiation with the energy of 40 MeV causes very significant changes in SiC JBS parameters even at the dose of $\sim 5 \times 10^{9}\,\mathrm{cm}^{-2}$.[6] The effect of proton irradiation with energies in the range 1.7–62.5 MeV on defect formation in 4H-SiC has been studied in a number of studies (see, for example, Refs. 7–10). Radiation hardness and defects created by proton irradiation in SiC were studied by capacity-voltage (*C-V*) and current-voltage (*I-V*) measurements, Deep Level Transient Spectroscopy (DLTS), electron paramagnetic (EPR) spectroscopy, photoluminescence, positron lifetime analysis, and positron annihilation spectroscopy.

Low frequency noise measurements are an effective and sensitive technique to study impurities and defects in semiconductors and semiconductor devices (see, for example, Refs. 11–13 and references therein). This method was already used to study the defects in non-irradiated Schottky diodes[14–16] and Schottky diodes irradiated with high energy electrons.[17]

In this work, we studied the electrical and noise properties of 4H-SiC JBS diodes after high energy (15 MeV) proton irradiation.

II. EXPERIMENTAL DETAILS

Commercial 4H-SiC Schottky diodes CPW4-1200S002B with a blocking voltage of 1200 V were irradiated by protons with an energy of 15 MeV in a MGTs-20 cyclotron. Since the mean free path of protons of this energy in SiC is about 1 mm, the defects were introduced into the material uniformly. The irradiation doses varied from 3×10^{12} to $1 \times 10^{14}\,\mathrm{cm}^{-2}$. The diodes were irradiated at room temperature in a pulse regime with the frequency of 100 Hz and a pulse duration of 2.5 ms. The average beam current density was within the range from 10 to 100 nA cm^{-2}.

The low-frequency noise was measured at room temperature in the frequency range 1–1000 Hz. The voltage fluctuations across the load resistor $R_L = 100\ \Omega$–$50\ \mathrm{k}\Omega$ connected in series with the sample were analyzed using a SR770 Network Analyzer. The background noise of the system was at least one order of magnitude smaller than the measured noise.

III. RESULTS AND DISCUSSION

A. Current voltage characteristics

Figure 1 shows the current voltage characteristics of a device under test (DUT) before and after irradiation with different doses.

The effect of 15 MeV proton irradiation on the current voltage characteristics is qualitatively similar to the effect of electron irradiation with the energy of 0.9 MeV discussed in Ref. 18. The exponential part of the characteristics is relatively weakly affected by irradiation. At low bias, irradiation leads to the increase in the leakage current. The resistance of the base layer sharply increases with the irradiation dose growth. However, the sensitivity of the samples to the proton and electron irradiation is essentially different. Similar changes in current voltage characteristics after electron irradiation occur at a dose of $\sim 4\times10^{16}\,\mathrm{cm}^{-2}$, i.e., at the dose $\sim$400 times higher than at proton irradiation.

As in the case of electron irradiation, the shape of the current voltage characteristics of proton irradiated diodes at low voltages $V \le 0.2$ V depends on *the ramp of the voltage scan dV/dt*.[18] Characteristics shown in Fig. 1 were measured at $dV/dt \ge 25$ mV/s. At $dV/dt \le 0.5$ mV/s, the current voltage characteristics at $V < 0.2$ V of non-irradiated and irradiated diodes are virtually the same. If the voltage step of a small amplitude $V \le 0.2$ V is applied to the irradiated diodes, the current decreases non-exponentially with time tending to the value measured in non-irradiated diodes. This time dependence is characterized by a very wide distribution of the relaxation times and is qualitatively the same as in electron irradiated diodes (see Fig. 2 in Ref. 18). The longest relaxation time observed in this decay process is in the range of a few tens of seconds.

Although this effect is definitely related to the deep levels created by irradiation, the specific mechanism of these processes is still unknown. Probably, this is the non-stationary current of electrons being trapped in the space charge region.

At relatively high forward voltages, $V \sim (0.7\text{–}1.5)$ V (Fig. 1), the current voltage characteristic is virtually linear and determined by the base resistance, R_b. In non-irradiated diodes, $R_b \approx 0.3\ \Omega$. Irradiation increases the base resistance up to $R_b \approx 3.3\,\Omega$ and $R_b \approx 5\times10^4\,\Omega$ for the doses $\Phi = 5\times10^{13}\,\mathrm{cm}^{-2}$ и $\Phi = 1\times10^{14}\,\mathrm{cm}^{-2}$, respectively.

At even higher voltages, the current voltage characteristic becomes nonstationary again, and its shape depends on the voltage scan ramp dV/dt. If a rectangular voltage pulse is applied to the diode, the current deceases with time during the pulse. The range of voltages where the characteristics are linear and stable depends on the irradiation dose.

Figure 2 shows current-voltage characteristics of the diode with the irradiation dose $\Phi = 1\times10^{14}\,\mathrm{cm}^{-2}$ at a large forward bias. Curves 1 and 2 correspond to $dV/dt \approx 0.015$ V/s and $dV/dt \approx 4.2$ V/s, respectively. Characteristics shown by curves 3 and 4 were measured in a pulse regime with pulse durations of 100 μs and 20 μs respectively. As seen from Fig. 2, the current voltage characteristics are super-linear at relatively large dV/dt and sub-linear at small dV/dt values.

The super-linear character of characteristics 3 and 4 in Fig. 2 can be explained by the effect of space charge limited current (SCLC).[19] Indeed, as a result of irradiation with a dose $\Phi = 1\times10^{14}\,\mathrm{cm}^{-2}$, the base resistance increased $\sim 1.5\times10^5$ times. This corresponds to the reduction of the electron concentration from $n_0 = 4\times10^{15}\,\mathrm{cm}^{-3}$ to $n_\Phi \approx 2.7\times10^{10}\,\mathrm{cm}^{-3}$ (the mobility reduction can be neglected for the defect concentration $\sim 4\times10^{15}\,\mathrm{cm}^{-3}$). Maxwellian relaxation time $\tau_M = \varepsilon\varepsilon_0/\sigma$ for the irradiated base material is $\sim 2.7\times10^{-7}$ s (here, $\varepsilon = 9.66$ is the permittivity of 4H-SiC, ε_0 is the permittivity in a vacuum, and σ is the conductivity (electron mobility μ is taken to be equal to 800 cm^2/V s[20])). The electron transit time $t_{tr} = L^2/\mu V$ at $V = 10$ V is about three orders of magnitude smaller. Therefore, we conclude that the SCLC regime dominates in proton irradiated diodes in a short time scale $\tau \le 100\ \mu$s.

In a longer time scale, the capture processes strongly affect the current-voltage characteristics. The dependence of current versus time during a relatively high forward voltage pulse $V = 9$ V is shown in Fig. 3.

It is seen that the current decay is characterized by the extremely wide range of time scales from at least $\sim 10^{-6}$ s to

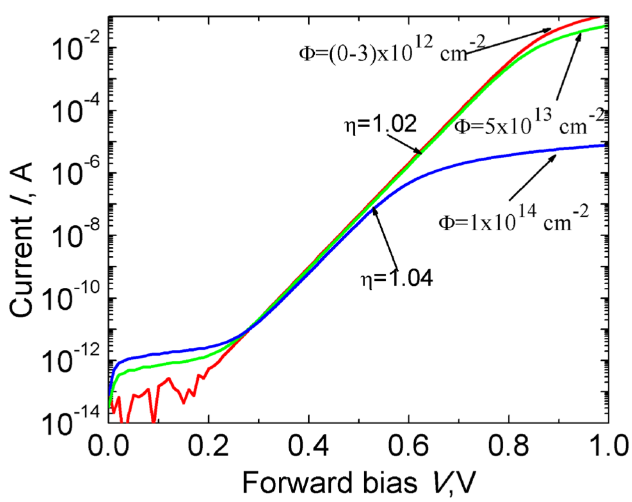

FIG. 1. Forward current voltage characteristics of DUT at different irradiation doses Φ.

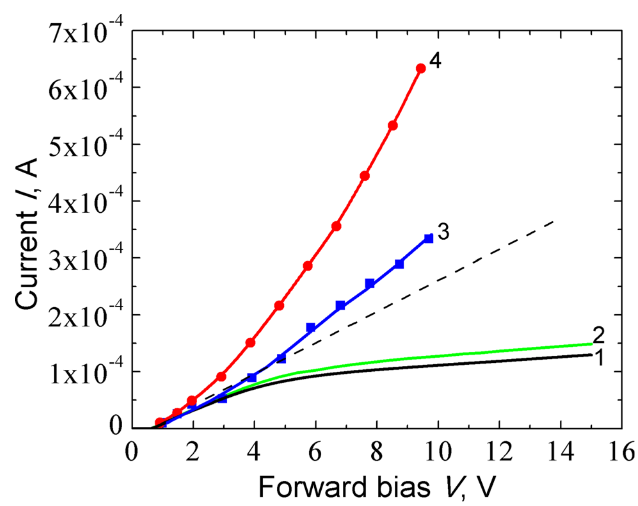

FIG. 2. Dynamic current voltage characteristics of the diode with the irradiation dose $\Phi = 1\times10^{14}\,\mathrm{cm}^{-2}$. 1—$dV/dt \approx 0.015$ V/s; 2—$dV/dt \approx 4.2$ V/s, 3—100 μs pulse; 4—20 μs pulse. Dashed line indicates the linear dependence.

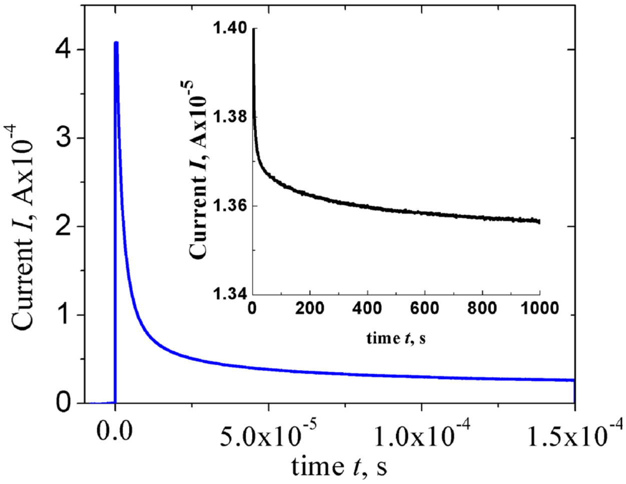

FIG. 3. Time dependence of the current decay during 9 V voltage pulse. Inset shows the same dependence for a longer time scale.

$>10^3$ s. It is noteworthy that the higher the bias, the larger the current reduction. Hence, we can conclude that this capture processes are field assisted. Note that the concentration of the traps is comparable to or even higher than the concentration of the injected electrons. This explains the reduction of the current below the level which corresponds to the ohmic resistance at lower voltages.

The dependences of the current decay at pulses of different amplitudes are shown in Fig. 4(a). It is seen that the higher the voltage, the higher the contribution of the long-time processes to the current decay.

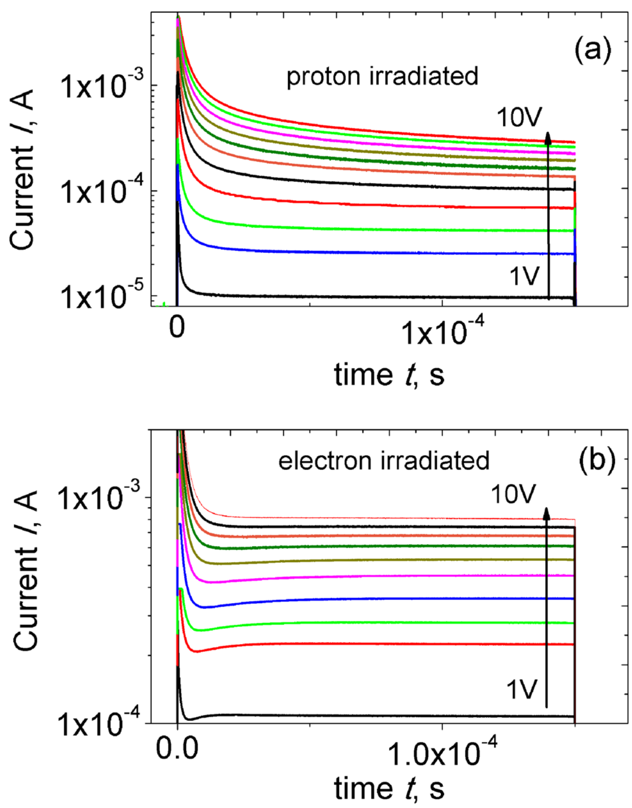

FIG. 4. Time dependences of the current for different forward voltages applied to a proton irradiated diode with the dose $\Phi = 1 \times 10^{14}\,\mathrm{cm}^{-2}$ (a) and an electron irradiated diode with the dose $\Phi_e = 4 \times 10^{16}\,\mathrm{cm}^{-2}$ (b).

Figure 4(b) shows the results of the same measurements on the identical diode irradiated by 0.9 MeV *electrons* with the dose $\Phi_e = 4 \times 10^{16}\,\mathrm{cm}^{-2}$.[18] This *electron* irradiation led to approximately the same increase in the base resistance as in proton irradiated diode shown in Fig. 4(a). As seen from Fig. 4(b), the relaxation process can be observed only in the time scale $\tau \sim 10\,\mu$s. These "fast" relaxation processes are observed due to the charging of the diode capacitance through the base resistance. Opposite to the proton irradiated diodes, electron irradiated diodes demonstrated that the current voltage characteristic is virtually linear up to $V = 10$ V. This qualitative difference in electron and proton irradiated samples with a similar base resistance is due to the different nature of the defects created by corresponding irradiation.

Figure 5 illustrates "the opposite process." The proton irradiated diode was kept for several minutes at $V = 10$ V. After that, the voltage dropped to the voltage $V = 1.5$ V, which corresponds to the linear part of the current voltage characteristic. As seen in Fig. 5, the current increases due to the generation of electrons from the traps. Also, note that in the process of resistance increase (Figs. 3 and 4), the opposite process is also non-exponential.

The results shown in Figs. 3, 4 and 5 indicate that the capture cross-section of traps generated by proton irradiation depends on the electric field due to the repulsive nature of traps (see, for example, Ref. 21).

Figure 6 shows the current voltage characteristics at different temperatures of the diode with irradiation dose $\Phi = 1 \times 10^{14}\,\mathrm{cm}^{-2}$.

As seen from Fig. 6, the higher the temperature, the higher the ideality factor. Note that at electron irradiation with an electron energy of 0.9MeV, which leads to approximately the same increase in the resistance of the base, the value of the ideality factor in the same temperature range remains constant.[18]

As expected, the resistance of the base decreases monotonically with increasing temperature. The temperature dependence of the resistance of the base shown in the inset of Fig. 6 indicates that the main contribution to the resistance decrease seems to be the thermal generation of electrons from the well-known $Z_{1/2}$ level with an activation energy of $0.5 < E_a < 0.69$ eV.[22,23]

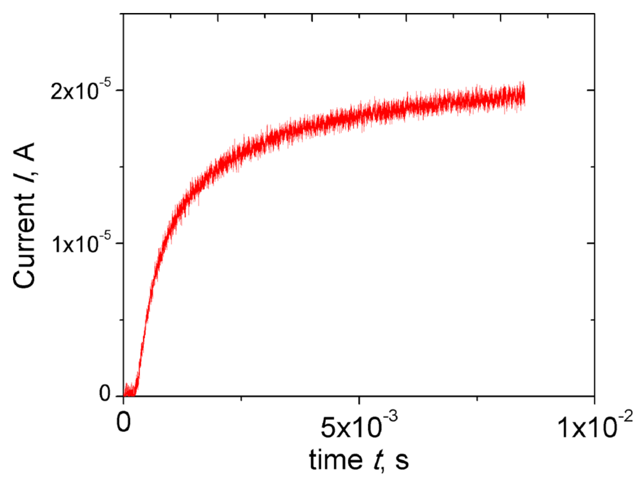

FIG. 5. Time dependence of the current when the diode is switched from $V = 10$ V to $V = 1.5$ V ($\Phi = 1 \times 10^{14}\,\mathrm{cm}^{-2}$).

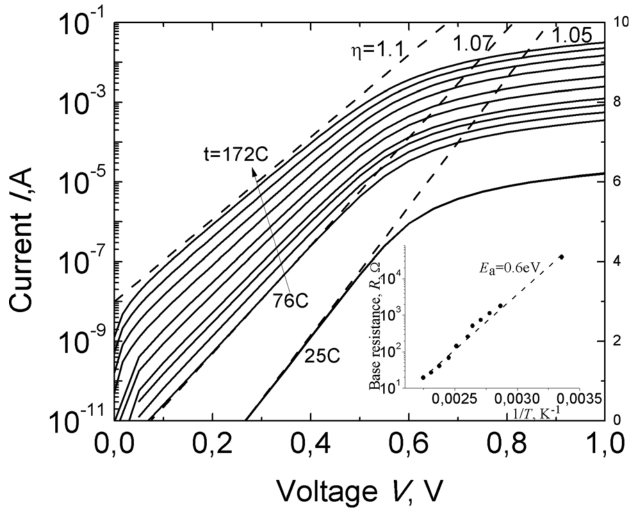

FIG. 6. Current voltage characteristics of the diode with irradiation dose $\Phi = 1 \times 10^{14}$ cm^{-2} at different temperatures. Inset shows the temperature dependence of the base resistance measured at $V = 1.5$ V.

At higher voltages, the shape of the current voltage characteristics and their temperature dependence become more complicated (Fig. 7).

At relatively low voltages on the sample $V \leq 2$ V, the current voltage characteristics in the temperature range (76–172 °C) are linear. At higher voltages and at room temperature, the characteristics are sublinear at a low ramp of voltage scan dV/dt (Fig. 2). Temperature increase leads to the transformation of this sub-linear characteristic to a super-linear one (Fig. 7). The higher the temperature, the lower the voltage, at which the super-linearity starts to manifest itself. A similar shape of the characteristics, but at higher voltages, was reported in Ref. 4 for non-irradiated SiC JBS diodes. This effect was attributed to the hole injection from the p-regions. In the irradiated diodes, the base resistance is orders of magnitude higher and the concentration of the majority carriers (electrons) is proportionally smaller. Therefore, it is natural to assume that the effect of the hole injections becomes important at lower voltages in the irradiated diodes at elevated temperatures.

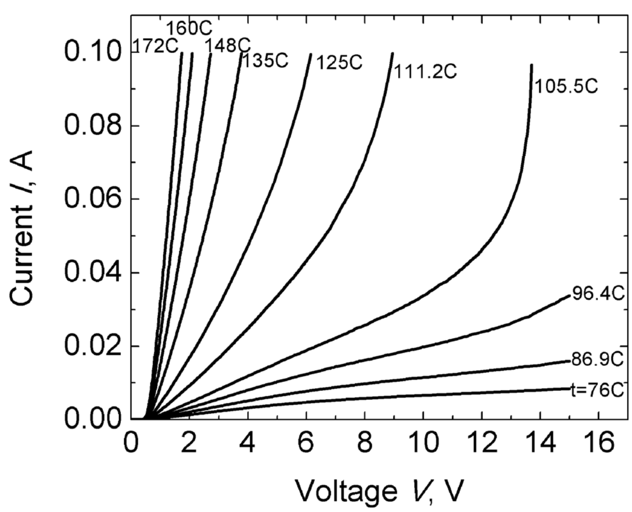

FIG. 7. Current voltage characteristics of the diode with irradiation dose $\Phi = 1 \times 10^{14}$ cm^{-2} at different temperatures at a high forward bias.

B. Low frequency noise

The low-frequency noise in JBS diodes, identical to those studied in this paper, were investigated in Ref. 16 in non-irradiated samples and in Ref. 17 in samples irradiated with electrons with an energy of 0.9 MeV. In non-irradiated samples, the noise had the form of the 1/*f* noise, both for currents corresponding to the exponential part of the current voltage characteristic and for the linear part of the *I*-*V* dependence.[16,17] As noted above, in the samples irradiated with electrons at the dose $\Phi = 4 \times 10^{16}$ cm^{-2}, the resistance of the base is approximately equal to the resistance of the base of the samples irradiated with protons at a dose of $\Phi = 1 \times 10^{14}$ cm^{-2}. It was shown in Ref. 17 that after irradiation with electrons, generation-recombination (GR) noise becomes predominant.

Figure 8 shows the noise spectra at different forward currents for the proton irradiated diode with the dose $\Phi = 1 \times 10^{14}$ cm^{-2}.

The current range, for which Fig. 8 shows the noise spectra, corresponds to the linear part of the current voltage characteristic (Fig. 1). At a given frequency, the current dependence of noise follows the $S \sim I^2$ law. As seen from Fig. 8, in the proton-irradiated samples, the slope of the frequency dependence of the noise spectral density is close to $S \sim 1/f^{0.5}$. In general, this type of spectra can be a result of contribution of several generation-recombination (GR) processes observed in the limited frequency range. However, opposite to the electron irradiated diodes, none of the well-defined Lorentzian spectra and the corresponding GR processes can be distinguished in the proton irradiated diodes. In comparison with non-irradiated diodes, the noise amplitude shown in Fig. 8 is 2–3 orders of magnitude higher (depending on frequency). It is obvious that this increase in noise is due to the defects created by irradiation. However, the character of the spectra, i.e., the absence of characteristic GR bumps does not allow us to identify and characterize the individual traps. This specific feature of the noise spectra in proton irradiated diodes indicates that in comparison with electron irradiation, proton irradiation creates a wider, more continuous spectrum of traps.

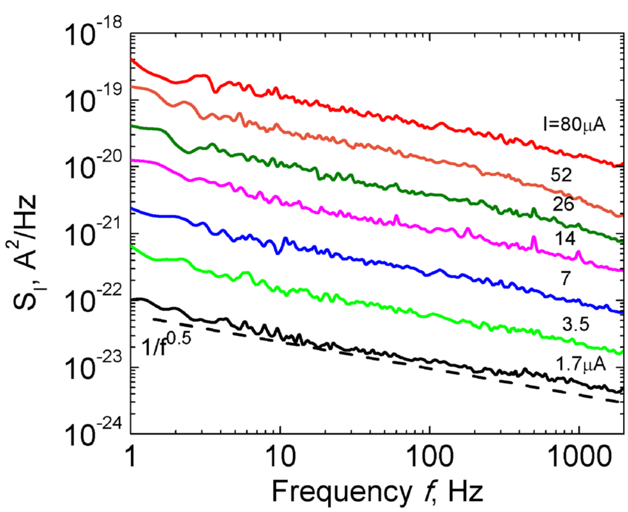

FIG. 8. Low frequency noise spectra of current fluctuations in the diode with the irradiation dose $\Phi = 1 \times 10^{14}$ cm^{-2} at different currents.

IV. CONCLUSIONS

The electrical and noise characteristics of class 1.2 kV 4H-SiC JBS diodes were studied after irradiation by protons with an energy of 15 MeV. The results are compared with the effect of high energy electron irradiation on the identical diodes studied in Refs. 17 and 18. Similar to electron irradiation, the proton irradiation mainly affects the resistance of the base and current voltage characteristic at small voltages $V < 0.2$ V. The exponential part of the characteristic is only weakly affected by proton and electron irradiation.

At low bias $V < 0.2$ V, the shape of the current voltage characteristics of both proton and electron irradiated diodes depends on *the ramp of the voltage scan dV/dt*. At high $dV/dt \geq 25$ mV/s, the current exceeds the steady state value several times. At $dV/dt \leq 0.5$ mV/s, the current voltage characteristics of non-irradiated and irradiated diodes are virtually the same.

At higher voltages $V > 4$–5 V, the super-linearity of proton irradiated diodes was found at room and elevated temperatures. We attribute this effect to the combination electron space charge limited current and hole injection from the *p*-regions.

Traps created in the diode base by proton irradiation are characterized by the wider distribution of the capture and emission characteristic times from 10^{-6} s to at least 10^{3} s. This is manifested by the slow relaxation processes observed in the pulse measurements of proton irradiated samples.

The noise spectra of electron and proton irradiated diodes are completely different. While the noise spectra of electron irradiated diodes contained several clear distinguished Lorentzians, which can be attributed to individual traps, the noise spectra of proton irradiated diodes are smooth and have an unusual slope $\sim 1/f^{0.5}$. This is the sign of more uniform energy distribution of traps created by proton irradiation.

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