Schottky diodes based on 4H-SiC epitaxial layers

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Abstract. Forward and reverse current-voltage (IV) characteristics of Cr-SiC (4H) Schottky diodes based on epitaxial layers with doping \((1-3) \cdot 10^{15} \text{cm}^{-3}\) were studied in the temperature range of 300-550 K. It is shown that in many cases the IV characteristics are close to ideal, but a significant spread of the forward IV characteristics of diodes manufactured in the same way on the same epitaxial layer was found, probably due to the spread of the Schottky barrier heights reaching 0.3 eV. Heating of the diode, as well as packaging, can also change the Schottky barrier height. An alternative explanation suggests the presence of a powerful shunt.

I. Introduction

Schottky diodes (SDs) based on silicon carbide are currently available on the market and can be used as, for example, rectifier diodes, ultraviolet radiation and short range ion detectors. In most cases, Schottky diodes based on weakly doped 4H-SiC epitaxial layers are used.

Earlier, the study of Schottky diodes based on highly doped \((\sim 10^{18} \text{cm}^{-3})\) epitaxial layers, as well as Lely 6H-SiC substrates, showed that the properties of Schottky diodes and, first of all, apparently, the Schottky barrier height, are determined by a number of factors (the method of preparing the surface of the semiconductor, the metal deposition temperature, the annealing temperature of the formed diodes, the orientation of the crystal, etc.) and they cannot be predicted, taking into account only the work function of the metal and electron affinity of semiconductor. Moreover, even under other equal conditions and on the same substrate there can be a significant variation in the current-voltage characteristics of neighboring diodes (up to 4 or more orders of magnitude in current in the region of the exponential dependence of current on voltage \(I=I_0 \exp \left(\frac{qU}{nkT}\right)\) [1]. Later, a similar effect was found in the study of Schottky diodes based on weakly doped \((\sim 2 \cdot 10^{15} \text{cm}^{-3})\) 4H-SiC layers [2]. In this paper, we continue to study the features of the IV characteristics of Schottky diodes based on weakly doped 4H-SiC epitaxial layers with a doping of \((1-3) \cdot 10^{15} \text{cm}^{-3}\).

2. Experimental

Study of the IV characteristics (IVs) of Schottky diodes based on two commercial 4H-SiC epitaxial layers with uncompensated donor concentration \(N_D - N_A = 3 \cdot 10^{15} \text{cm}^{-3}\) and with thickness of 9 \(\mu\text{m}\) (substrate N72915) and with \(N_D - N_A = (1-2) \cdot 10^{15} \text{cm}^{-3}\) and with thickness of 26 \(\mu\text{m}\) (substrate N330) is presented. Epilayers were grown by CVD on a highly-doped 4H-SiC wafer. The Cr films for Schottky contacts (with Cr thickness of 0.1 \(\mu\text{m}\)) were deposited in vacuum by thermal evaporation at a temperature close to room temperature (RT). Diodes on the substrate N72915 are made of two diameters: 8 mm and 1 mm and on the substrate N330 with a diameter of 1.2 mm. All Schottky diodes were manufactured under identical conditions, but the diodes on the substrate N72915 with a diameter
of 1 mm were packaged after the study of their IV characteristics and after package SDs were re-characterized. The IV characteristics were measured in DC mode in the temperature range 300-550 K.

3. Results and discussion

Figure 1 shows the IVs at room temperature of diodes on a substrate N72915 (N_{p,N} = 3 \cdot 10^{15} \text{ cm}^{-3}).

The forward IVs of diodes of large diameter (D 8 mm. Figure 1, left column) show a spread in voltages (corresponding to a particular value of forward current) reaching 0.3 V at relatively high currents, when the influence of the residual resistance of the diode is noticeable (Figure 1 a). At low forward currents, the spread of IVs is also significant, but their comparison is difficult, since the IVs are not ideal (Figure 1c). The reverse IVs of large-diameter diodes in the range of 0.1-10 V are in some cases described by power-law dependences of the form I=U^m with an exponent of m~0.3 (Figure 1 e, curve 1), but the correspondence of the values of forward and reverse currents is not always unambiguous (not always, the greater the forward current, the greater the reverse; Figures 1 c, e).

The forward IVs of diodes of small diameter (D 1 mm, Figure 1, right column) before packaging are practically the same for both large and small currents (Figures 1 b, d, curves 1ini-3ini (initial)). At low currents over 9 orders of magnitude the forward current depends exponentially on the voltage I=I_0 \exp(qU(nkT)) and is characterized by ideality factor n~1.05 (Figure 1 d). There is a significant parallel shift of the forward IVs at low currents towards lower voltages (the n values of all diodes are approximately preserved) as a result of the packaging, and a spread of the IVs of the diodes appears: the total effect reaches (0.2-0.4) V in voltage and up to 6 orders of magnitude in current; at large forward currents, the spread is not so significant (Figures 1 b, d, curves 1-3). The reverse IVs of small-diameter SDs in the range of 0.1-10 V can be described by power-law dependences of the form I=U^m with an exponent of m=0.2-0.3; in addition, there is an unambiguous correspondence between the values of forward and reverse currents (Figures 1 f, d).

Thus, according to the results of the study at room temperature of Schottky diodes on the substrate N72915, we can conclude:

*the small-diameter diodes can be considered close to ideal according to such criteria as the value of the ideality coefficient n of the forward current and the type of the IV characteristics at the reverse bias, corresponding to the model of the current caused by thermionic emission [3] both before and after packaging; packaging leads to a significant shift and spread of the IV characteristics of the diodes while maintaining the value of n (n~1.05) of all diodes;

*although the IV characteristics of some large-area SDs (D 8 mm) demonstrate some signs of ideal characteristics (the proximity of the n value to n=1 in a limited current range for two diodes (Fig. 1 c, curves 5, 6) and the proximity of the exponent m of the reverse IV characteristics (or their fragments) for some diodes to the value m=0.25, which is characteristic of the current due to thermionic emission (Figure 1 e), however, the most distinct effect is the spread of the IV characteristics at large forward currents;

*it can be assumed that the main reason for the spread of the IVs is the difference in the Schottky barrier height in both cases (for diodes with a diameter of 8 mm and with a diameter of 1 mm); this difference reaches, for example, ~0.3 eV if the I_o difference in ideal diodes reaches 6 orders of magnitude (a similar assumption was made in [1] (see Figure 1), where similar effects were observed).

It is known [3] that to solve the problem of the Schottky barrier height value, it may be more informative to study the IVs at different temperatures. In this paper, such a study was carried out for SDs with a diameter of 1.2 mm on the N330 substrate with a similar doping of the n-layer (N_{p,N} = (1-2) \cdot 10^{15} \text{ cm}^{-3}).

At room temperature there is a spread of forward IV characteristics in the region of the exponential dependence of current on voltage (as for diodes on the substrate N72915). Unfortunately, the ideality factor n is slightly higher than ideal (Figure 2 a shows forward IVs for 4 different Cr-SiC(4H) Schottky diodes on the same substrate characterized by ideality factor n=1.47 (diode N1), n=1.35 (diode N2), n=1.15 (diode N4), n=1.35 (diode N8) at RT=19°C - 22°C before heating. The reverse current at voltages up to 100 V also exceeds the current of the ideal diode (Figures 2 e, f, curves 1).
Figure 1. Forward (a-d) and reverse (e, f) IV characteristics at room temperature RT (17°C-25°C) of Cr-SiC (4H) Schottky diodes on substrate N72915. Left column (a, c, e) – are IV characteristics of eight Schottky diodes with a diameter of 8 mm. Right column (b, d, f) – are IV characteristics of three Schottky diodes with a diameter of 1 mm before packaging (1ini, 2ini, 3ini, - empty symbols) and after packaging (1, 2, 3, - filled symbols). The slope of curve 9 (e) is an indicator of the 1/3 power law behavior. Note that lin-lin scales are used for (a) and (b), semilog scales are used for (c) and (d), and log-log scales are used for (e) and (f).
Temperature measurements of the forward and reverse IV characteristics in the temperature range 300-550 K were carried out for diodes N4 (Figures 2 c, e) and N8 (Figures 2 d, f), for which the IV characteristics demonstrate the maximum spread at the lowest values of n. Figure 2,b shows temperature dependencies of the parameters $J_o$ and n (insert) of the forward current $J = J_o \exp(qV/nkT)$ and reverse current $J_{rev} (100V)$ at reverse voltage 100 V for SDs N4 and N8, and the values of parameters $J_o$, n and $J_{rev} (100V)$ at room temperature after heating to 546 K followed by cooling.

Forward IV characteristics in the temperature range 300-450 K remain exponential (Figures 2 c, d). The ideality coefficient n in course of heating approximately retains its value. The dependences of $J_o$ on the inverse temperature in the first approximation can be considered as exponential. For diode N4 characterized by lowest n value (n=1.15) the activation energy of pre-exponential factor $J_o$ is $\approx 1$ eV; for diode N8 characterized by n=1.3 the activation energy of $J_o$ is $\approx 0.6$ eV (Figure 2 b). The IV characteristic for diode N4 at room temperature after heating followed by cooling shifted towards smaller voltages with n somewhat decreasing (to n=1.1).

Reverse IV characteristics in course of heating became similar at high temperatures (500-550 K) for both diodes (N4 and N8), drawing together and they can be described by power-law dependences $I \sim U^m$, characterized by m=1 at $U_{rev} < 0.1$ V and by m=0.24-0.26 in the range 1V < $U_{rev} <100$ V (Figures 2 d, f). The activation energy of the reverse current at high temperatures and at voltage $U_{rev}=100$V (there m=0.24) is $\approx 1$ eV for diode N4 (Figure 2 b, curve 4rev). For both diodes, there is a significant reduction in reverse currents at room temperature after heating to 550 K (Figure 2 e, f, curves 1c).

In the framework of the model of the current caused by thermionic emission, the activation energy of the current of an ideal Schottky diode is determined mainly by the Schottky barrier height. Thus, the Schottky barrier height is approximately equal to 1 eV according to the results of temperature studies of the IV characteristics of the N4 diode, which is close to the ideal diode. It is more difficult to estimate the height of the Schottky barrier for a less ideal N8 diode (n=1.3), but it does not appear to be much different than 0.6 eV. Heating up to 550 K of the N4 diode apparently led to some reduction in the barrier height.

It seems that the temperature studies of the IV characteristics are consistent with the measurement data at room temperature. Namely, the studied Schottky diodes based on weakly doped (1-3)·10^{15} cm^{-3}) 4H-SiC epitaxial layers demonstrate the possibility of a noticeable difference (up to 0.3 eV) in the potential barrier height, even for diodes on the same epitaxial layer manufactured in the same way, as well as a decrease in the height of the barrier due to relatively low-temperature annealing.

In [4], when studying IVs at forward bias of diodes based on 6H-SiC pn structures, currents were found that were interpreted as excess, due to the shunting of the main (principle) pn junction by another parasitic diode (connected in parallel to the main diode) with a lower barrier height and a smaller area. Later, similar currents were found both in pn structures based on 4H-, 3C-SiC and in diodes based on the Schottky barrier at the metal-SiC (6H, 4H) contact [5-10]. This interpretation is based on the characteristic form of the forward IV characteristic, when an excess current is observed at low voltages, and as the forward voltage increases, starting from a certain value, the IV characteristic coincides with the characteristic of the main diode.

In the case of the diodes presented in this paper (as in the case of the diodes presented in [1]), it is difficult to say with certainty whether the currents observed at forward bias are due to the characteristics of the main Schottky diode in all cases, or they can be excess due to shunts. It seems that the second interpretation is acceptable, but the shunts in this case should be sufficiently ‘powerful’, capable of passing large currents, i.e. comparable in resistance (and, apparently, in area) with the main diode. In this case, the spread of the IV characteristics will be determined by a combination of both the potential barriers and the areas of the main diode and shunt.
Figure 2. IVs (a, c-f) and parameters $J_0(T^{-1})$, $n(T)$ and $J_{rev}(100\,V)=f(T^{-1})$ (b) for Cr-SiC (4H) SDs with a diameter 1.2 mm on the N330 substrate: (a) forward IVs of four SDs at RT=19°C – 22°C before heating; (b) temperature dependences of the parameters $J_0$ and $n$ (insert) of the forward current $J=J_0\exp(qV/nkT)$ (curves 4 and 8) and reverse current $J_{rev}(100\,V)$ at voltage 100 V (curves $4_{rev}$ and $8_{rev}$) for SDs N4 (curves 4 and $4_{rev}$) and N8 (curves 8 and $8_{rev}$); points 4c, 8c, $4_{rev}c$, $8_{rev}c$ are the values of $J_0$, $n$ and $J_{rev}$ (100 V) at RT after heating to 546 K; straight line (4) is linear fit with slope 1 eV; IVs at forward (c, d) and reverse (e, f) bias at T: 292K→ 340K→396K→442K→490 →546K (curves from 1 to 6, respectively) and at RT (292K) after heating followed by cooling (curves 1c) for SDs N4 (c, e) and N8 (d, f), m is the parameter of the power law dependence $I=U^m$. 

Journal of Physics: Conference Series 2103 (2021) 012235 doi:10.1088/1742-6596/2103/1/012235
4. Conclusion

The study of the IV characteristics of Cr-SiC (4H) Schottky diodes based on weakly doped epitaxial layers showed that in many cases both the forward and reverse IV characteristics are close to ideal, corresponding to the model of the current due to thermionic emission, and also revealed a significant spread of the forward IV characteristics at both small and large currents. The spread is observed for diodes manufactured in the same way on the same epitaxial layer and is probably due to the spread of the Schottky barrier heights reaching 0.3 eV. The effects of annealing and changes in the IV characteristics of diodes as a result of packaging were also detected.

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