Influence of Different Surface Morphologies on the Performance of High-Voltage, Low-Resistance Diamond Schottky Diodes

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Abstract — Vertical diamond Schottky diodes with blocking voltages $V_{BD} > 2.4$ kV and on-resistances $R_{ON} < 400$ m$\Omega$cm$^2$ were fabricated on homoepitaxially grown diamond layers with different surface morphologies. The morphology (smooth as-grown, hillock-rich, polished) influences the Schottky barrier, the carrier transport properties, and ultimately the device performance. The smooth as-grown sample exhibited a low reverse current density $J_{Rev} < 10^{-4}$ A/cm$^2$ for reverse voltages up to 2.2 kV. The hillock-rich sample blocked similar voltages with a slight increase in the reverse current density ($J_{Rev} < 10^{-3}$ A/cm$^2$). The calculated 1-D breakdown field, however, was reduced by 30%, indicating a field enhancement induced by the inhomogeneous surface. The polished sample demonstrated a similar breakdown voltage and reverse current density as the smooth as-grown sample, suggesting that a polished surface can be suitable for device fabrication. However, statistical analysis of several diodes of each sample showed the importance of the substrate quality: a high density of defects both reduces the feasible area and increases the reverse current density. In forward direction, the hillock-rich sample exhibited a secondary Schottky barrier, which could be fit with a modified thermionic emission (TEM) model employing the Lambert W-function. Both polished and smooth samples showed nearly ideal TEM with ideality factors 1.08 and 1.03, respectively. Compared with the literature, all three diodes showed nearly ideal TEM with ideality factors $1.08$ and $1.03$, respectively. The smooth as-grown sample exhibited a low reverse current density as the smooth as-grown sample, suggesting that a polished surface can be suitable for device fabrication. However, statistical analysis of several diodes of each sample showed the importance of the substrate quality: a high density of defects both reduces the feasible area and increases the reverse current density. In forward direction, the hillock-rich sample exhibited a secondary Schottky barrier, which could be fit with a modified thermionic emission (TEM) model employing the Lambert W-function. Both polished and smooth samples showed nearly ideal TEM with ideality factors 1.08 and 1.03, respectively. Compared with the literature, all three diodes exhibit an improved Baliga figure of merit for diamond Schottky diodes with $V_{BD} > 2$ kV.

Index Terms — Baliga figure of merit (BFOM), diamond, Lambert W-function, power electronics, power semiconductor devices, Schottky diodes.

I. INTRODUCTION

With its unique electrical and thermal properties, diamond possesses a high potential for the use in power electronic devices. In particular, a high thermal conductivity of 2000 W/(m K), the hole mobility of up to 3800 cm$^2$/(V s), and the theoretical dielectric strength of 10 MV/cm [1]–[3] make diamond a viable choice for addressing key issues (e.g., switching losses, heat dissipation, and high breakdown voltages) of power electronic devices.

Schottky barrier diodes (SBDs), either vertical SBD (VSBD), pseudovertical (pVSBD), or planar (pISBD), are commonly used to assess the feasibility of diamond as a material for power electronic applications [3]. Although it has been shown that individual diodes are capable of blocking high voltages ($V_{BD} > 10$ kV [4]), withstanding high electric fields ($E_{Max} = 9.5$ MV/cm [5]) or of transporting high currents ($I_{Max} > 20$ A [6]), there has been no reported research on diodes exhibiting both high breakdown voltages $V_{BD}$ and high currents $I_{Max}$ to this date. Umezawa [3] identified missing edge terminations, high reverse current through electrically relevant defects, and a nonoptimized device design as key causes for their performance far below the theoretical expectations.

Additionally, both surface termination [4], [7] and surface morphology play an important role in the performance of diamond SBDs. Umezawa et al. [8] identified nonepitaxial crystallites on the surface as a cause for increased leakage currents. Furthermore, Teraji et al. [9] analyzed the influence of mid-gap states on the reverse current $I_{Rev}$ but did not observe any influence of the surface roughness on $I_{Rev}$.

However, the analysis of SBDs on polished epitaxial surfaces has not been investigated. In this article, we, therefore, present the performance of high voltage ($V_{BD} > 2.4$ kV) vertical SBDs with low specific ON-resistances ($R_{ON} = 300 – 400$ m$\Omega$cm$^2$) fabricated on homoepitaxial diamond with different surface morphologies (Hillocks on surfaces, smooth as-grown, polished). The diodes are compared with published diamond diodes exhibiting similar blocking voltages (Twitchen et al. [10]) and exhibit an approximately seven-time increase in the Baliga figure of merit $BFOM = V_{BD}^2/(R_{ON}A)$.

Recently, diamond diodes fabricated with the same methods as presented in this article were used to demonstrate the application in a nonisolated buck converter [11].

II. EXPERIMENTAL DETAILS

The vertical diamond Schottky diodes were realized using 17–28-μm-thick, unintentionally doped ($N_A < 10^{15}$ cm$^{-3}$) homoepitaxial diamond i-layers, which were grown on thick
Fig. 1. Microscopic image of the sample S1 (a) before and (b) after growth of a 28-μm intrinsic diamond layer. The position of the diode is marked in yellow. (c) In the X-ray topography image, defects (D) and growth sector boundaries (GB) can be identified. (d) Image shows an overlay of (b) and (c).

Fig. 2. (a) Overview, (b), (d) detailed microscopic images, and (c) WLI surface roughness of sample S2 after growth of a 17-μm-thick intrinsic diamond layer with a reduced CH₄/H₂ ratio of 3%.

(300 μm) highly boron doped \(N_A \approx 2 \times 10^{20} \text{ cm}^{-3}\), type IIb), commercial high pressure high temperature (HPHT) substrates. The i-layers were grown in a homemade microwave plasma-enhanced chemical vapor deposition (MWPECVD) system (for details of the deposition system, see [12] and [13]). Prior to growth, the polished substrates were acid cleaned in a 3:1 mixture of sulfuric acid and nitric acid at 250 °C for 90 min, with a subsequent methanol rinse to remove any particles. In order to minimize the influence of any polishing damage, a H₂-plasma etch was conducted for 5–40 min directly before the initiation of the growth. The growth conditions were optimized to reduce residual boron doping and to create surfaces with a reduced roughness. They were as follows: A gas mixture with a CH₄/H₂ ratio of 4% (sample S1) and 3% (samples S2 and S3) with an additional 0.15% O₂/H₂ [14] was used, at a process pressure of 200 mbar. The microwave power was adjusted in the range of 2.1–2.3 kW to stabilize a substrate temperature of roughly 800 °C. During growth, the samples were rotated to minimize any anisotropic effects arising from the direction of the gas flow.

After growth, the samples were cleaned in the mixture of sulfuric acid and nitric acid once more to remove any graphitic parts of the backside and to enhance the oxygen termination of the surface. Apart from sample S3, which was mechanically polished on an iron plate to flatten the hillocks observed after growth, all samples were used as-grown. To reduce the subsurface polishing damage, the polished sample S3 was etched for 10 min in a 2.2-kW H₂ plasma at 800 °C in the MWPECVD prior to contact fabrication. Microscopic images of the layers used for device fabrication are shown in Figs. 1(b), 2(a), and 3(b) for the samples S1, S2, and S3, respectively.

The ohmic contacts were realized with a stack of TiPtAu deposited by electron-beam evaporation on the backside of the highly boron doped substrates. A subsequent rapid thermal annealing in N₂ atmosphere for 60 s at 850 °C yielded an ohmic contact with a contact resistivity of \(\rho = 1 \times 10^{-5} \text{ Ω cm}^2\). Before evaporation of the Schottky metal, a short oxygen plasma ashing was used to enhance the oxygen termination of the surface. Using standard lithography techniques, several Schottky diodes with diameters \(d = 100, 200, 300 \mu\text{m}\) were fabricated on each of the samples. Electron-beam evaporated titanium was used as a Schottky metal with platinum as a diffusion stop layer and gold as a capping layer. Exemplarily, Fig. 3(c) shows the diodes of the sample S3.

The electrical properties of the vertical Schottky diodes were analyzed by capacitance–voltage measurements (C–V) and current–voltage measurements (I–V) under forward and reverse bias. To avoid arcing at high reverse voltages, the diodes were immersed in Fluorinert during reverse I–V measurement.

III. RESULTS AND DISCUSSION

A. Sample Morphology

All three diodes discussed in this article were chosen to have a similar maximum blocking voltage of \(V_{BD} \approx 2.5 \text{ kV}\) despite being processed on diamond samples with different surface morphologies.

In Fig. 1, a microscopic image of the hillock-rich sample S1 is presented Fig. 1(a) before and Fig. 1(b) after growth. On the right half of the sample, a higher density of growth hillocks is observed. These larger hillocks presumably arise from defects which are present in the substrate [15]: the overlay of the X-ray topography of S1 [Fig. 1(c)] with the microscopic image in Fig. 1(d) suggests a correlation of
the growth hillocks with the defects present in the substrate. A detailed analysis of the hillock formation is outside the scope of this article. The area in the center of the left half of the sample is characterized by a rough surface (rms roughness 12 nm) with less hillocks. The relatively high roughness is believed to originate from the high CH₄/H₂ ratio of 4%. The diode on S1, which is analyzed in this article, is situated in the rough but hillock-free region.

Since a rough surface can have negative effects on the electrical characteristics such as field enhancement or secondary Schottky barriers, sample S2 was grown with a reduced CH₄/H₂ ratio of 3%. The microscopic images in Fig. 2(a) and (b) show a significantly smoother surface compared to the sample S1, with an rms roughness < 0.8 nm [Fig. 2(c), measured with a white light interferometer (WLI)]. Furthermore, no prominent growth hillocks are observable compared to the sample S1, which is analyzed in this article, is situated in the rough but hillock-free region.

Although the third sample S3 was grown under the same conditions as S2, a surface with a high density of hillocks and etch pits was observed [Fig. 3(a)], rms roughness > 50 nm]. A low-quality substrate with a high density of dislocations is assumed to be the cause for these undesired dislocations: The substrate’s dislocations penetrate into the epitaxial layer during growth and become sites for preferential etching and hillock growth [15]. These defects are assumed to be “killer defects” [16]–[18] for the Schottky diode and can cause a premature breakdown. To reduce undesired effects of the surface morphology on the diode performance, ca. 3 μm were removed by polishing of the top surface [Fig. 3(b)], leaving a surface with an rms roughness of 1.5 nm. Note that due to a slight misorientation during polishing, the surface is inclined by 0.13°, as can be seen by the nonpolished area in the lower left corner of the sample.

**B. Electrical Measurements**

1) C–V Characteristics: Fig. 4(a) shows the capacitance C per area A from sample S2 for three differently sized diodes. There is no variance in C/A in between the diodes with different diameters. Fig. 4(b) plots the calculated A²/C² versus the reverse voltage. The net doping concentration NA – ND is calculated with a linear fit between 0 and 1 V using NA – ND = 2/(qε₀ε₆d) × (−d(A²/C²)/dV)⁻¹, where q denotes the elementary charge, ε₀ the vacuum permittivity, and ε₆ the diamond’s permittivity [19]. This yields NA – ND = 2.6 × 10¹⁴ cm⁻³ for all three diodes of sample S2. With NA – ND = 6.8 × 10¹⁴ cm⁻³ and NA – ND = 2.0 × 10¹⁴ cm⁻³, respectively. Sample S1 and sample S3 exhibit similar net doping concentrations.

From the built-in voltage ψₘ given by the x-axis intercept of the linear fit of the A²/C² data, the Schottky barrier height ϕₜ is calculated by ϕₜ = ψₘ + kₜT + ϕₐ [19]. Here, ϕₘ = (Eₜ − Eₜ)/q ≈ 0.36 eV [20] is the energy difference between valence band and Fermi level, with the temperature T and Boltzmann’s constant kₜ. NextNano software was employed for the simulation of ϕₘ using the corresponding net doping concentration. Both samples S1 and S2 have similar ϕₜ = 1.45 eV ± 0.01 eV, whereas the polished sample S3 exhibited a much larger barrier height of ϕₜ = 1.80 eV ± 0.05 eV (averaged over six diodes each).

With a simple plate capacitor model to estimate the depletion depth W = ε₆dA/C, the differential slope of A²/C² can be used to plot NA – ND versus W. As can be seen in Fig. 4(c), the net doping concentration is nearly constant over the probed depth. Due to their smaller absolute capacitance values, the smaller diodes are affected more heavily by signal noise.

The NA – ND value as measured with C–V was confirmed by cathodoluminescence (CL) measurements [21] on other layers grown under the same condition, which yielded the same net doping concentration for both measurement types. The analysis of the CL data is not the scope of this article and will be discussed elsewhere.

2) I–V Characteristics: To study the electrical properties of the Schottky contact, the forward I–V characteristics are analyzed. Fig. 5 compares the I–V characteristics of the three high-voltage blocking diodes of the samples S1, S2, and S3 with the data reported by Twitchen et al. [10] for a diamond Schottky diode with a similar breakdown voltage. Both diodes on sample S2 (smooth as-grown) and sample S3 (smooth after
polishing) show a very good agreement with the thermionic emission (TEM) current transport model

\[ J_{\text{TEM}} = A^* T^2 e^{-\frac{q\varphi}{k_B T}} \left( e^{\frac{q\varphi}{k_B T}} - 1 \right) \]  

represented by the dashed lines in Fig. 5. The model includes an ohmic term \( R_{\text{ON}A} \) to account for the series resistance of the i-layer. \( A^* = 4 \pi m^* k_B^2 / h^2 = 90 \, \text{A cm}^{-2} \text{K}^{-2} \) is the Richardson constant for diamond [22]. With an ideality factor of \( n = 1.03 \) and \( n = 1.08 \) for the smooth as-grown and polished sample, respectively, the current transport is nearly purely thermionic. The barrier height, on the other hand, is noticeably higher on the polished sample S3 (\( \varphi_B = 1.51 \, \text{eV} \)) than on the smooth as-grown sample S2 (\( \varphi_B = 1.38 \, \text{eV} \)). This might be a consequence of the additional H\(_2\) etch step on S3 after polishing.

The inset of Fig. 5 shows a lin–lin plot of the same \( I–V \) data. The diode on the polished sample S3 exhibits a reduced \( \text{ON} \)-resistance of \( R_{\text{ON}A} = 300 \, \text{m\Omega cm}^2 \) compared to \( R_{\text{ON}A} = 440 \, \text{m\Omega cm}^2 \) of the diode on the smooth as-grown sample S2. Considering the different layer thicknesses \( d_{\text{i-layer}} \), the series resistivity \( \rho = R_{\text{ON}A} / d_{\text{i-layer}} \) of the diode on the smooth as-grown sample S2 is roughly twice the series resistivity of the diode on the polished sample S3. This is surprising, since their quite similar doping level would only account for a difference of 5\% in the resistivity. Future work will include the investigation of the temperature dependence of \( R_{\text{ON}A} \) as well as Hall measurements to further examine the reduced series resistance of the polished sample.

When comparing the \( I–V \) data of the three samples from this work with the data reported by Twitchen et al. [10], the high \( \text{ON} \)-resistance of the latter is evident. From the \( I–V \) slope at higher voltages (\( U > 6 \, \text{V} \)), an \( R_{\text{ON}A} \approx 2000 \, \text{m\Omega cm}^2 \) is estimated for Twitchen’s diode.

The \( I–V \) characteristic of the diode on the rougher sample S1 exhibits two different slopes in the exponential region. In Fig. 5, the two regions with differing slopes are marked with light red backgrounds (labeled as I and II), with a detailed view shown in Fig. 6. As discussed in [23]–[25] for SiC and diamond Schottky diodes, respectively, this can have its origin in localized patches with a secondary, lower Schottky barrier height \( \varphi_{B,\text{low}} \). Defives et al. [23] used an iterative approach to fit (1) to the two different regions, using the theoretically expected series resistance to extract the barrier heights and ideality factors. Note that due to the implicit form of (1), this iterative approach does not allow for a combined \( I–V \) model for the two regions.

As was shown by Banwell and Jayakumar [26] and later adapted by Jung and Guziewicz [27], an explicit analytical solution exists for (1) using the Lambert W-function. As was recently analyzed by Olih [28], extracting the Schottky diode parameters by the Lambert W-function reduces both the determination error and the number of accuracy influencing factors. Ortiz-Conde et al. [29] used the explicit nature of the Lambert W-function to model the multieponential behavior of solar cells.

A similar approach will be used in the following to assess the Schottky parameters of the diode on the “hillock sample” S1. The total current through the diode \( I_{\text{Tot}} \) is modeled by the sum of the current through \( N \) branches and given by

\[ I_{\text{Tot}}(V) = \sum_{i=1}^{N} \frac{n_i k_B T}{q R_{\text{ON},i}} W_0 \left( \frac{I_{\text{Sat},i} R_{\text{ON},i}}{n_i k_B T} \right)^{\frac{q(V + I_{\text{Sat},i} R_{\text{ON},i})}{n_i k_B T}} - I_{\text{Sat},i} \]  

For each branch \( i \), the following parameters are used: the saturation current \( I_{\text{Sat},i} \), the active Schottky contact area \( A_i \), the ideality factor \( n_i \), the series resistance \( R_{\text{ON},i} \), and the Schottky barrier height \( \varphi_{B,i} \). \( W_0(x) \) is the Lambert W-function [30] and \( \beta = q / (k_B T) \).

Formula (2) with \( N = 2 \) was used to fit the \( I–V \) data of sample S1 by minimizing the squared sum of the relative errors

\[ \sigma = \sum_{V=V_{\text{min}}}^{V_{\text{max}}} \left( (I_{\text{Sat},1,\text{exp}}(V) - I_{\text{Sat},1}(V))/I_{\text{Sat},1,\text{exp}}(V) \right)^2 \]  

between \( V_{\text{min}} = 0.39 \, \text{V} \) and \( V_{\text{max}} = 2.9 \, \text{V} \). Introducing an additional shunt conductance \( G_P \) to the model (2) did not improve the fit (\( G_P \to 0 \)) and is consequently omitted for further analysis.

To overcome the ambiguity of the determination of the contact areas \( A_i \), the following procedure is proposed: Assuming a constant specific \( \text{ON} \)-resistance \( R_{\text{ON},i} / A_i = \text{const.} \) for all current paths, the area \( A_i \) can be found by \( A_i = (R_{\text{ON},i} / R_{\text{ON,Tot}}) \cdot A_{\text{Tot}} \).
using the combination of parallel resistances $R_{ON,Tot} = (\sum_{i=1}^{N} R_{ON,i})^{-1}$ with $A_{Tot} = \sum_{i=1}^{N} A_{i}$.

Fig. 6 shows the experimental $I-V$ data of the diode on S1 and the model fit using (2) with $N = 2$. The main contribution to the current flow at higher voltages is characterized by a high ideality factor of $n_1 = 1.43$. Under the assumption $R_{ON,i} A_{i} = \text{const.}$, $A_{1}$ accounts for 99.994% of the total diode area, with a Schottky barrier of $\varphi_{B,1} = 1.14$ eV. The current flow in the low-voltage ($V < 0.6$ V) region is governed by a small area patch ($A_2 = 0.006 \% \times A_{Tot} \approx 2 \mu m^2$) with a reduced effective Schottky barrier of $\varphi_{B,2} = 0.89$ eV and a slightly reduced ideality factor $n_2 = 1.23$. Several other diodes of S1, with diameters $d$ of both 100 and 200 $\mu m$, exhibit a similar $I-V$ characteristic regarding $n_1, n_2, \varphi_{B,1}$, and $\varphi_{B,2}$. Regardless of $d$ and the fit total specific ON-resistance $R_{ON,Tot} A_{Tot}$, $A_2$ is found to be very similar for all these diodes and in the range $1 \mu m^2 < A_2 < 3 \mu m^2$. Due to the small number of different diameters, no clear area-specific influence could be identified. Since the influence of horizontal current spreading is omitted in the previous analysis, the areas $A_2$ might be overestimated.

Despite the increased thickness of the i-layer of S1, the specific ON-resistance $R_{ON,Tot} A_{Tot} = 350$ m$\Omega$cm$^2$ of the diode presented in Fig. 6 is comparable to the ones measured for the samples S2 and S3. For $V > 2$ V, $R_{ON,Tot} A_{Tot}$ is slightly underestimated by the fit as can be seen in the linear scaled inset in Fig. 6.

Note that although the fit barriers $\varphi_{B,i}$ drastically depend on the assumption made for the determination of the areas $A_i$ for the model fit, both $n_i$ and $R_{ON,Tot} A_{on,i}$ are unaffected. Discarding $R_{ON,i} A_i$ and assuming, for example, equal areas for all current paths (i.e., $A_i = A_{Tot}/N$) yields $\varphi_{B,1} \approx \varphi_{B,2} \approx 1.13$ eV with the same $n_i, R_{ON,Tot} A_{Tot}$ and $\sigma$.

We also compared the results for $n, \varphi_B$ and $R_{on,A}$ when fitting the $I-V$ data of the diodes of the samples S2 and S3 to both (1) and (2). Both models yield very similar results with relative variations smaller than 2%. Consequently, the modified Lambert W-model (2) constitutes a valid approach to characterize the Schottky contact properties of dual barrier diodes.

The Schottky barriers determined by $I-V$ are all smaller than those determined by $C-V$. This trend is understandable when considering that an effective barrier $\varphi_{B,eff}$ governs the current transport during $I-V$ measurement. Small patches with a reduced barrier height or a random distribution (e.g., Gauss like) of barrier heights reduce the effective barrier [31], [32] as measured by $I-V$. As was discussed by Tung [32], a Gauss-like distribution of barrier heights yields a dependence of the barrier heights $\varphi_{B,eff}(n) = \varphi_B^0 - 3(n-1)V_{bb}/2$ on the ideality factor where $V_{bb}$ denotes the band bending. Fig. 7 shows $\varphi_B(n)$ for several diodes of the three samples. For the dual barrier diodes of S1, $\varphi_{B,2}(n)$ is displayed. The $\varphi_B^0$ of S1 and S2 are comparable to the barrier heights obtained by $C-V$, whereas $\varphi_B^0$ of the polished sample S3 is still notably smaller than the value measured by $C-V$. This conduction mechanism might be attributed to a different surface modification due to the H$_2$ plasma treatment of S3 after polishing. A different treatment (e.g., longer plasma exposure or etching with H$_2$/O$_2$ plasma) may clarify this observation.

3) Reverse $I-V$ Characteristics: The reverse $I-V$ characteristics of the diamond Schottky diodes are presented in Fig. 8. The data reported by Twitchen et al. [10] is shown for comparison. The diode on the smooth as-grown sample S2 and the diode on the polished sample S3 exhibit a very low leakage current density $J_{Rev} < 10^{-4} A/cm^2$ for reverse voltages up to 2.2 kV. An irreversible breakdown occurred at $V_{BD} = 2.5$ kV and $V_{BD} = 2.6$ kV, respectively. The diode on the sample exhibiting a rougher surface with hillocks (sample S1) shows a slightly higher leakage current over the entire voltage range. Breakdown occurs at $V_{BD} = 2.4$ kV.

The breakdown occurred in the punchthrough (PT) regime for all three diodes, since the theoretical epilayer thickness required for the non-PT case [19] $W_{PT} = (2e_d V_{BD}/(q(N_A - N_D)))^{1/2}$ $> d_{layer}$. Considering the reciprocal punchthrough factor as defined by Chicot et al. [33] $\eta = d_{layer}/W_{PT}$, the diodes in this article have a PT factor of $\eta \approx 0.6$ (S1) and $\eta \approx 0.2$ (S2, S3), close to the optimal value of $\eta \approx 0.7$ [33]. With $\eta < 0.07$, the factor of Twitchen’s diode is much lower which is induced by the low doping density $N_A - N_D < 10^{13} cm^{-3}$ [10]. The low doping density results in a higher ON-resistance and lower current density in forward direction.

When calculating the maximum electric field in a simplified, 1-D model using [19] $E_{Max} = V_{BD}/d_{layer} + q(N_A - N_D)d_{layer}/2e_d$, sample S1 (hillocks) and S3 (polished) exhibit a similar breakdown field of $E_{Max} \approx 1.2$ MV/cm, whereas sample S2 (smooth) withstands a roughly 30% higher field with $E_{Max} \approx 1.6$ MV/cm.
The reduced breakdown field likely arises from the rough surface (S1) and the high defect density (S2). Due to a field enhancement caused by the inhomogeneous surface of S1, the local field at breakdown may even be higher than $E_{\text{Max}}$ as calculated by the simple 1-D model. Since no edge termination was applied for all three diodes, a field enhancement is expected for all three devices [34].

A statistical analysis of the reverse $I$–$V$ characteristics of several diodes of each sample is shown in Fig. 9. The cumulative probability (CP) of the breakdown voltage $V_{BD}$ for S2 shows no prominent dependence on the diode diameter [Fig. 9(a)]. The highest blocking diodes are statistical outliers. As can be seen in Fig. 9(b), CP($V_{BD}$) of the small diodes on S3 is notably shifted to higher breakdown voltages. This implies a higher density of “killer defects” on the polished sample [35], limiting the area feasible for diode fabrication. The diameter-dependent CP ($V_{BD}$) of S1 behaves similar to CP ($V_{BD}$) of S2 and is therefore, not shown.

The comparison of CP ($V_{BD}$) of all three samples in Fig. 9(c) shows a slightly steeper slope of CP ($V_{BD}$) for the smooth as-grown sample S2 when compared to the polished sample S3, indicating a more homogeneous crystal quality. The rough sample S1 exhibits generally lower breakdown voltages, which may be attributed to local field enhancement caused by the surface roughness.

To analyze the reverse current, Fig. 9(d) plots CP ($V = V_0$) with $J_{\text{Rev}}V_0 > 10^{-4}$ A/cm². Both the untreated samples S1 and S2 show a similar behavior, while the polished sample S3 exhibits a pronounced increased probability for a higher reverse current density. The diameter-dependent CP ($V = V_0$) of S3 (not shown) is similar to CP ($V_{BD}$) in Fig. 9(b), indicating that the high defect density of the substrate is also responsible for the higher reverse current density.

No prominent relationship was established between the reverse $I$–$V$ characteristics and the Schottky barrier or the ideality factor.

To conclude the statistical analysis, polishing a sample could potentially allow the fabrication of high-voltage blocking diodes. However, due to the higher reverse current density and the restricted feasible device area on low-quality substrates, only substrates with a low defect density enable a reasonable device fabrication.

As a possibility to classify the quality of the present work, Fig. 10 plots $R_{\text{ON}}A$ versus $V_{BD}$ (“Baliga plot”) for various diamond diodes published to date [3], with a comparison of the theoretical limits for unipolar power devices on Si, SiC, and diamond. Note that for some of the data points from [3], no related publication could be found (half-filled circles). These seemingly “better” diodes (regarding the BFOM) are, therefore, omitted in the comparison in this article. The diodes presented in this article outperform the diode presented by Twitchen et al. [10], with a BFOM of $(18, 15, 21)$ MW/cm² for the samples S1, S2, and S3, signifying an approximately seven-time increase over Twitchen’s diode (3 MW/cm²).

Table I summarizes the sample parameters and the data gathered from the $I$–$V$ and $C$–$V$ measurements.

### Table I

| Sample Details and Electrical Properties |    | S1 | S2 | S3 |
|------------------------------------------|----|----|----|----|
| Quantity                                 |    |    |    |    |
| i-layer thickness (μm)                    |    | 28 | 17 | 23 |
| Surface quality                          |    |    | Hillocks | Smooth | Polished |
| RMS roughness (nm)                       |    | 12 - 20 | <0.8 | 1.5 |
| Schottky barrier (eV) (IV)                |    | (0.89) | 1.14 | 1.38 | 1.51 |
| Schottky barrier (CV)                     |    | 1.45 | 1.45 | 1.80 |
| Ideality factor                          |    | (1.23) | 1.43 | 1.03 | 1.08 |
| $R_{\text{on}}A$ (mΩ·cm²)                |    | 330 | 440 | 300 |
| $V_{BD}$ (kV)                             |    | 2.4 | 2.5 | 2.6 |
| 1D $E_{\text{Max}}$ (MV/cm)              |    | 1.2 | 1.6 | 1.2 |
| BFOM (MW/cm²)                            |    | 18 | 15 | 21 |
| PT Factor $\eta$                         |    | 0.6 | 0.2 | 0.2 |

**IV. Conclusion**

In this article, three homoepitaxially grown diamond layers with different surface morphologies were employed for the fabrication of high-voltage Schottky diodes. Even though the diodes from all three samples were able to block at least 2.4 kV, the diodes on both the polished and the hillock-rich sample (S3 and S1) showed a reduced...
performance with respect to the maximum breakdown field ($E_{\text{Max}} \approx 1.2 \text{ MV/cm}$). Presumably, this is attributed to the high defect density of the epitaxial layer (S3) and a field enhancement due to the rough surface (S1).

The diodes fabricated on the smooth as-grown sample S2, whose homoepitaxial layer was grown on a high-quality diamond substrate, exhibited a breakdown field of $E_{\text{Max}} \approx 1.6 \text{ MV/cm}$. Similar to the polished sample S3, a low reverse current density $I_{\text{rev}} < 10^{-4} \text{ A/cm}^2$ was measured for reverse voltages up to 2.2 kV. The rectification ratio of S2 was as high as 10, with an ON-resistance of $R_{\text{on}}A = 440 \text{ m\Omega cm}^2$. This is approx. five times lower than the ON-resistance of diamond diodes with similar breakdown voltages [10], yielding the BFOM = 15 MW/cm². Due to their lower ON-resistance, both the diode on the polished and on the hillock-rich samples exhibited an even higher BFOM of 21 MW/cm² and 18 MW/cm², respectively. Further work is required to assess whether the reduced series resistance of the polished diode is affected by the surface treatment.

A statistical analysis of several diodes of each sample showed that even though a low-quality substrate with a polished surface is suitable for high-voltage blocking diodes, the high density of crystal defects both reduces the feasible device area and increases the reverse current density.

By employing the Lambert W-function, the current transport of dual barrier diodes was modeled with high accuracy. Future work may explore the influence of the diode’s diameter on the calculated patches of reduced barrier heights, examining any influence of local surface inhomogeneities on the current transport.

To conclude, we showed that the surface morphology and the crystal quality play an important role in the device performance of diamond Schottky diodes. We expect a further increase in the breakdown voltage if a suitable edge termination is applied.

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