Defect and Diffusion Forum
ISSN: 1662-9507, Vol. 452, pp 33-38
doi:10.4028/p-epPB1m

Submitted: 2025-09-13
Revised: 2026-01-14
Accepted: 2026-02-23
Online: 2026-05-18

DC and RF Local Electrical Properties of Macrostepped 4H-SiC Surface Probed by Scanning Spreading Resistance Microscopy and Scanning Microwave Impedance Microscopy Modes

Rosine Coq Germanicus[1,a*] and Gabriel Ferro[2,b]

[1]Normandie Univ, Ensicaen, Unicaen, CNRS, CRISMAT UMR6508, 6 Bvd Marechal Juin, Caen, France

[2]Laboratoire des Multimatériaux et Interfaces, CNRS UMR5615, Université Claude Bernard Lyon1, 6 rue Victor Grignard, 69622 Villeurbanne, France

[a*]rosine.germanicus@unicaen.fr, [b]gabriel.ferro@univ-lyon1.fr

Keywords: 4H-SiC, surface structuring, macrostepped morphology, AFM, SSRM, sMIM.

Abstract. Local electrical properties of a 4H-Silicon Carbide SiC(0001) 4°off macrostepped surface, obtained after liquid Si melting in a SiC/Si/SiC sandwich configuration, are investigated by Atomic Force Microscopy (AFM) in both DC and RF modes. On the same sample, macrosteps that are wide enough for allowing spatial resolution of the signal from terraces and step risers, but also some unreacted areas with standard flat surface (without macrosteps) are characterized. Scanning Spreading Resistance (SSRM, DC mode) reveals homogeneous conductivity on the wide terraces of the 4H-SiC(0001) macrosteps. On unreacted areas, which contain many step risers, the resistance is found higher than on the wide terrasses but it is also noisier. In addition, the AFM-RF scanning Microwave Impedance Microscopy (sMIM) mapping confirms the previous results by revealing lower conductivity on the unreacted areas than on the terraces of the macrosteps. Based on these results, some points defects located at the step risers which contribute negatively to the electrical properties of 4H-SiC(0001) surface are identified and electrically characterized.

Introduction

In 4H-SiC(0001) MOSFETs, the channel mobility can be limited by the electrically active defects at the SiO_2/SiC interface [1]. Some experimental studies suggest that these defects tend to localize at the step edges of the step-and-terrace surface structure generated by the use of 4° off-axis crystals [2-4]. The separation between the effect of step risers and terrasses was possible thanks to the demonstration of macrostepping control of 4H-SiC(0001) 4°off surface using liquid Si melting in a SiC/Si/SiC sandwich configuration [5, 6]. These results were obtained by using spatially resolved optical responses, not directly related to the electrical properties of the presence of defects at the step risers. In fact, the local electrical impact of these defects remains to be characterized, a crucial factor that can contribute to elucidating and understanding the origin of the low channel mobilities in 4H-SiC MOSFETs.

In this paper, electrical properties of a 4H-SiC(0001) 4°off macrostepped surface are investigated by Atomic Force Microscopy (AFM) to reveal local electrical properties as a function of the surface morphology. Two complementary AFM electrical modes are applied to explore the surface properties: the widely used Scanning Spreading Resistance (SSRM) mode, which is a DC mode [7], and the more original scanning Microwave Impedance Microscopy (sMIM) mode, which is a RF AFM-mode [8].

AFM Electrical Modes and the Macrostepped SiC Sample

AFM measurements were conducted on a Bruker ICON Dimension AFM, with Scanning Spreading Resistance (SSRM) mode and scanning microwave impedance microscopy (sMIM). SSRM is based on the local electrical conduction of the current between a conductive AFM tip and the sample when a V_{DC} bias is applied. In fact, during this electrical contact mode, a conductive AFM tip contacts the surface, forming a nano-Schottky junction. A logarithmic amplifier records the current from the tip through the sample to the back contact under an applied DC bias (Fig. 1). Using ultra-hard tips (like doped diamond tip) prevents tip deformation and ensures reliable data.

The scanning Microwave Impedance Microscopy (sMIM) is an AFM-RF mode, based on the interaction of an incident 3 GHz microwave signal with the studied surface [6]. The sMIM mode uses this incident RF microwave interacting with the surface, requiring no electrical contact with the AFM chuck. This mode simultaneously maps the surface topography and local electrical properties of the probed materials, producing four channels: topography, deflection, sMIM-C and sMIM-R signals (Fig. 2). The two sMIM signals correspond to the real and imaginary parts of the tip-sample admittance changes.

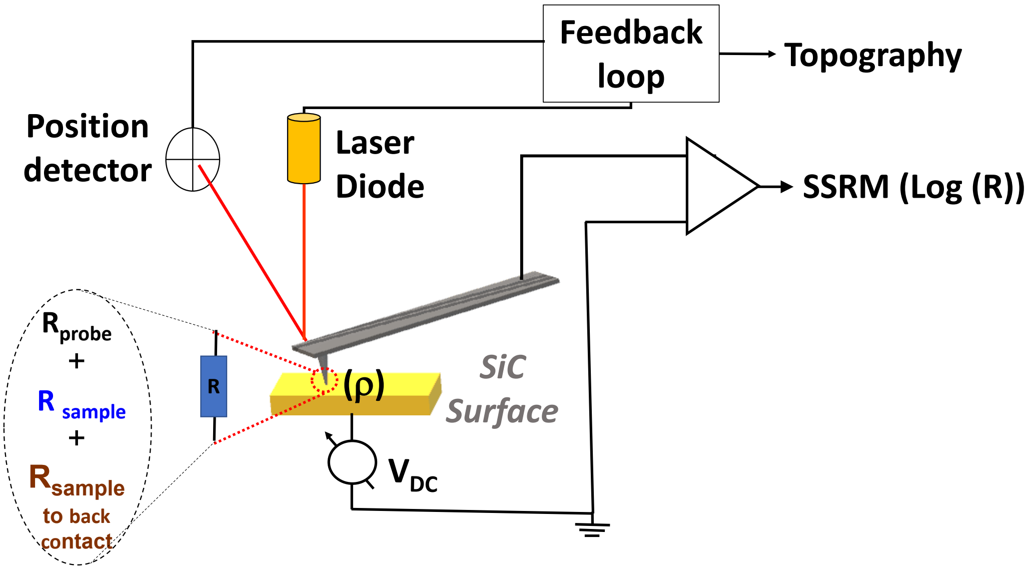


Fig. 1. Schematic of a Scanning Spreading Resistance (SSRM) mode based on an AFM.

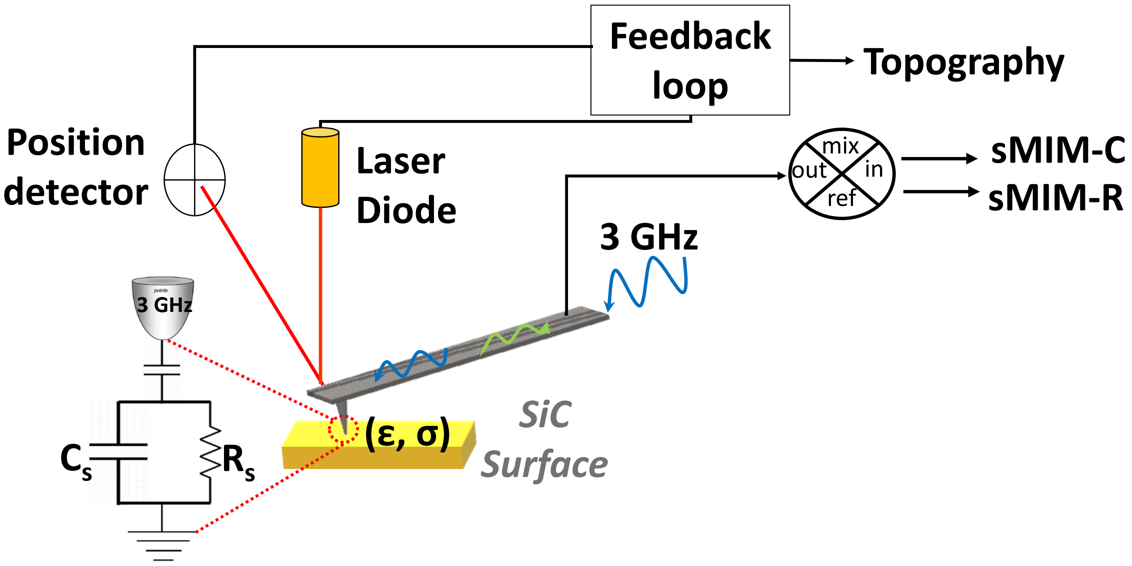
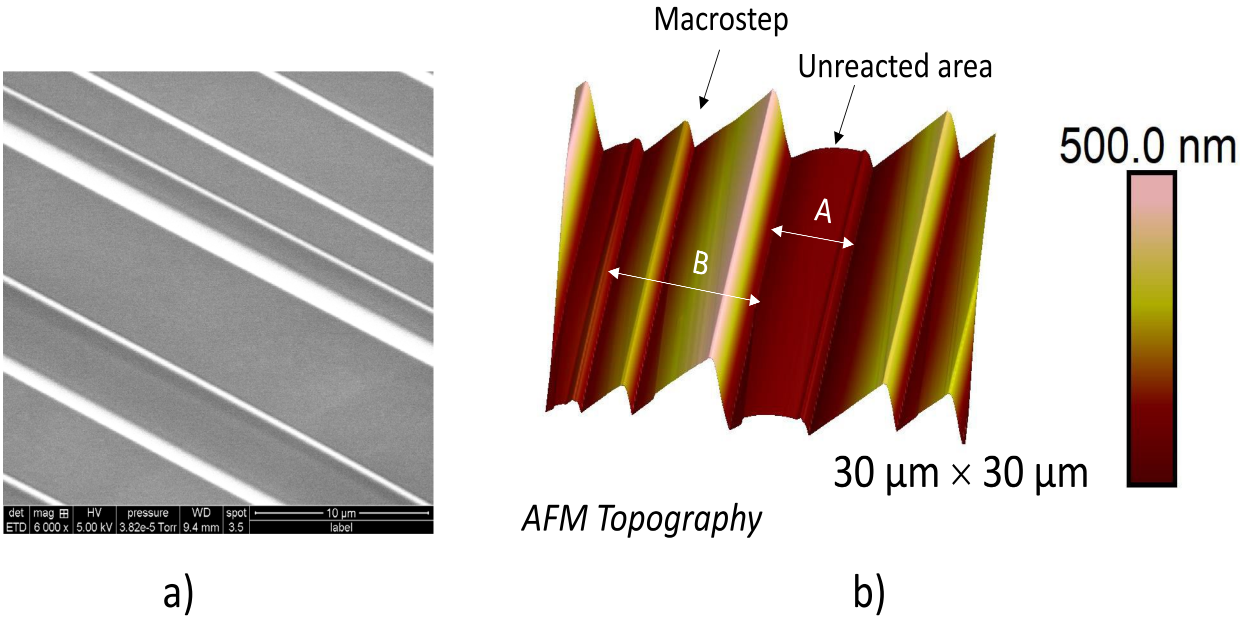


Fig. 2. Schematic of a scanning Microwave Impedance Microscopy (sMIM) mode based on an AFM.

The fabrication procedure for obtaining a macrostepped surface is described in details in ref [4-6]. The sample is obtained from a SiC(wafer)/Si(30µm)/SiC(wafer) sandwich stack treated at 1550°C for 1h. The vertical thermal gradient naturally forming inside the stack generates a carbon transport through the 30 µm thick liquid Si, from the bottom SiC wafer (hot) to the top SiC wafer (cold). This leads to the formation of parallel macrosteps on the dissolved (cold) surface (Fig. 3.a). Note that it may leave some so-called unreacted areas, denoted A in Fig. 3.b, which correspond to local zone where the surface did not evolve yet to macrosteps despite being subjected also to dissolution. Though longer treatment times than 1h allows eliminating these unreacted areas, we used here only 1h treatment in order to take advantage of the presence of both types of areas (unreacted (A) and macrosteps (B)) in the same AFM scans for proper comparison of their local electrical properties.



a) b)

Fig. 3. SiC macrostepped surface a) SEM view of the SiC surface after thermal treatment and b) 3D view of the AFM topography.

Results: Electrical AFM Mappings

The AFM height profile (Fig. 4.a) along one line allows easy identification of such unreacted area (A) when comparing to the adjacent macrosteps (B) displaying regular altitude increase and decrease. In order to probe local resistance of the SiC, a conductive diamond coating tip is used in contact with the SiC surface (Fig. 4.a). Prior to SSRM scanning, electrical AFM spectroscopy tests were carried out to determine the optimum V_{DC} values for measuring the current flowing through the nano-Schottky contact between the conductive tip and the sample in passing mode. For this sample an optimum V_{DC} was determined at -7 V applied to the sample. Using this optimum value of V_{DC}, the recorded SSRM mapping is shown in Fig. 4.b. A measured resistance profile line is reported in the SSRM map. While resistance is homogeneous on the wide terraces of the macrosteps (location B), the electrical signal is noisier for the unreacted area (A). In addition, the average resistance looks higher in area A than in area B. The pixel histogram analysis of the measured resistances, reported in Fig. 4.d, for both areas confirms this trend. For the macrosteps (B), the mean resistance is log (R) = 7.1 Ω with a standard deviation of 0.2 Ω, whereas for areas unreacted the distribution of resistances shows an average resistance about log (R) = 7.4 Ω with a standard deviation of 0.3 Ω. Some pixels indicate resistances of up to log (R) = 8.5 Ω. Note that, since the SSRM mode is performed in contact mode and, due to the sharp geometry of the 4H-SiC(0001) 4°off macrostepped surface, the systematic resistance increase at step riser can be attributed to the effective tip-sample contact, which becomes very weak at the extremity of the step. The SSRM measurements indicate that, when the probe is positioned on zone A, the current flow between the tip and the sample is significantly hindered. The measured resistance comprises the tip resistance (approximately 10^3 Ω) and the resistance of the back contact between the sample and the AFM chuck. For the entire scanned area, these two contributions remain constant; thus, any variation in the measured resistance reflects differences in the local electrical properties. To confirm these results, sMIM method is also used.

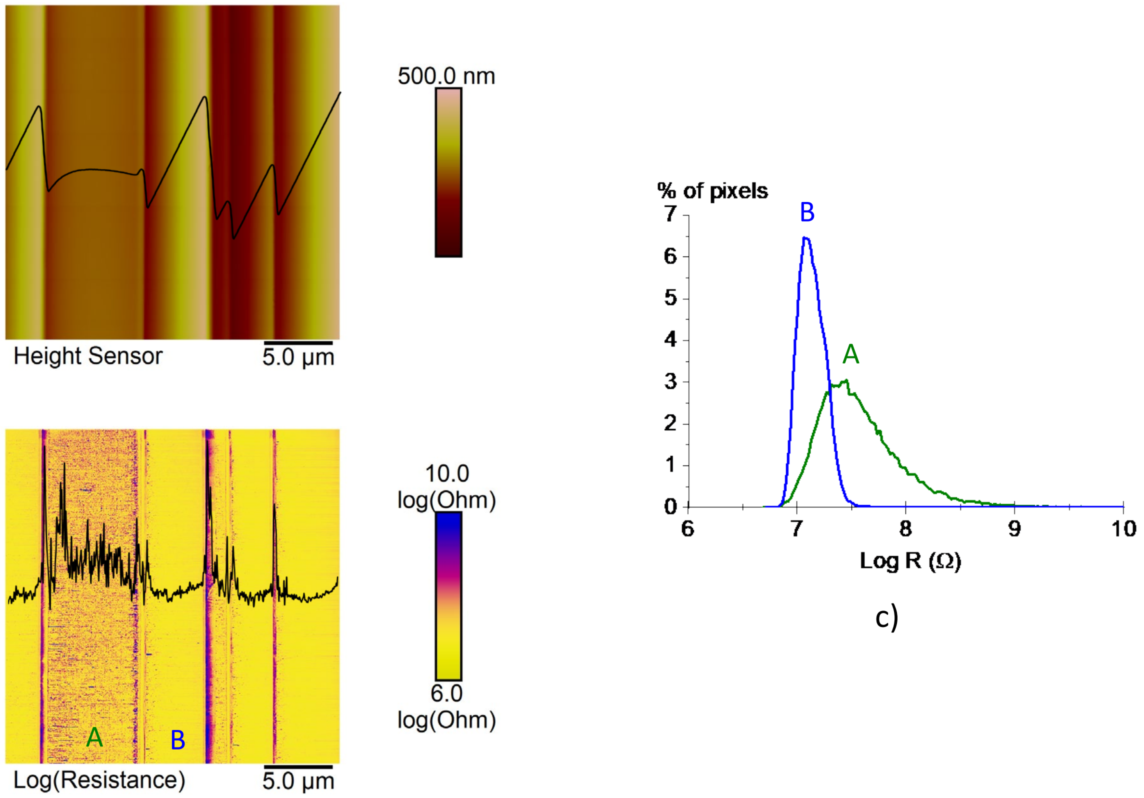


Fig. 4. DC electrical conduction by AFM-SSRM, V_{DC} = -7 V is applied to the sample: a) topography of the scanned surface 25 µm × 25 µm, 512 × 512 pixels, b) measured Log(R) cartography by SSRM and c) pixel histograms of log (R) on the areas A and B.

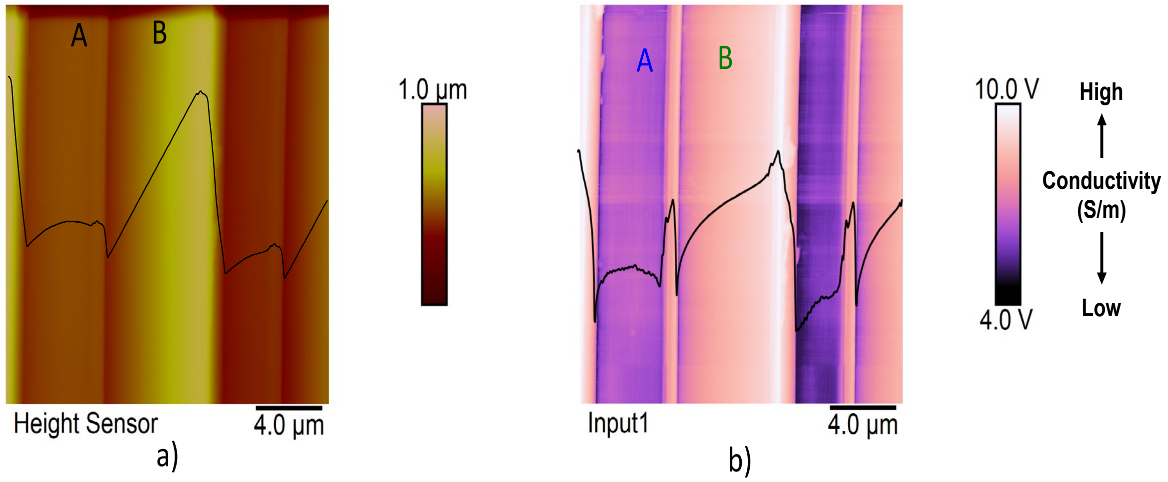


Fig. 5. RF electrical conduction by AFM-sMIM, a) topography of the scanned surface 20 µm × 20 µm, 512 × 512 pixels, b) measured sMIM-C cartography.

When sMIM mapping is performed on the 4H-SiC(0001) macrostepped surface, unreacted areas (A) and macrosteps (B) can be also identified (Fig. 5.a). Based on the interaction of the incident microwave signal with the surface and subsurface of the material, sMIM is sensitive to the RF conductivities of a nanoscale volume of material beneath the shielded tip. In Fig. 5.b, the sMIM-C signal (imaginary part of the complex impedance, measured after a calibration step) is related to the relative electrical capacitance of the material underneath the AFM nano-waveguide tip. sMIM results shows that the unreacted areas (A) are less conductive than the terraces of the macrosteps (B) which correlates well with the SSRM results.

Discussion

From the results obtained, a clear correlation between the local electrical conduction properties both in DC (SSRM) and in RF (sMIM) based on an AFM is demonstrated: unreacted areas present a higher and noisier local resistance than the macrosteps. As schematized in Fig 6, the main difference between unreacted areas and macrosteps is the density of step risers at the surface: it is much higher on unreacted areas. Then step risers can contains defects that negatively affect the electrical properties of 4H-SiC surface.

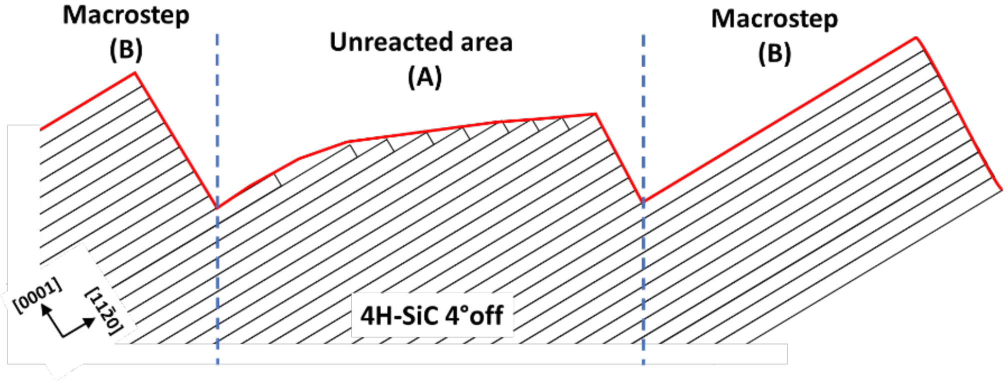


Fig. 6. Cross sectional schematic view of the 4H-SiC(0001) 4°off macrostepped sample surface showing after liquid Si melting i) an unreacted area (A) with a high density of step risers and ii) macrosteps (B) with ideally no step riser except at their extremity.

Conclusion

Local electrical properties of a 4H-Silicon Carbide SiC(0001) 4° off macrostepped surface, obtained by structuring using a SiC/Si/SiC sandwich with a liquid Si interlayer, are probed with two AFM-based modes. The DC mode, SSRM, reveals that the local resistance of the unreacted areas is higher and noisier compared to the macrostepped areas. The RF mode, sMIM, confirms this trend with a lower conductivity for the unreacted area. These investigations demonstrate the correlation between surface morphology of the4H-Silicon Carbide SiC(0001) 4° off macrostepped and electrical behavior, providing complementary insight into local transport mechanisms of the SiC at the nanoscale.

References

[1] P. Fiorenza et al., "Electron trapping at SiO2/4H-SiC interface probed by transient capacitance measurements and atomic resolution chemical analysis," Nanotechnology, vol. 29, no. 39, p. 395702, Jul. 2018, doi: 10.1088/1361-6528/aad129.

[2] J. Woerle et al., "Two-dimensional defect mapping of the SiO2/4H-SiC interface," Phys. Rev. Mater., vol. 3, no. 8, p. 084602, Aug. 2019, doi: 10.1103/PhysRevMaterials.3.084602.

[3] M. Camarda, J. Woerle, V. Souliere, G. Ferro, H. Sigg, U. Grossner, and J. Gobrecht, Analysis of 4HSiC MOS Capacitors on macro-stepped surfaces, Mater. Sci. Forum, 897, (2017), 107–110, doi: 10.4028/www.scientific.net/MSF.897.107.

[4] N. Alyabyeva et al., "Nanoscale Mapping of Sub-Gap Electroluminescence from Step-Bunched, Oxidized 4H-SiC Surfaces," physica status solidi (b), vol. 260, no. 5, p. 2200356, 2023, doi: 10.1002/pssb.202200356.

[5] Y. Jousseaume et al., "Controlled Macrostepping of Si-Face 4°off 4H-SiC over a Large Area via Liquid Si-Induced Reconstruction," Materials Science Forum, vol. 1089, pp. 9–14, 2023, doi: 10.4028/p-5p6o3j.

[6] Y. Jousseaume, P. Kumar, M. E. Bathen, F. Cauwet, U. Grossner, and G. Ferro, “Surface Structuring of Patterned 4H-SiC Surfaces Using a SiC/Si/SiC Sandwich Approach,” Materials Science Forum, vol. 1124, pp. 7–12, 2024, doi: 10.4028/p-auZ0OI.

[7] P. Fiorenza et al., “Complementary Two Dimensional Carrier Profiles of 4H-SiC MOSFETs by Scanning Spreading Resistance Microscopy and Scanning Capacitance Microscopy,” Solid State Phenomena, vol. 358, pp. 45–49, 2024, doi: 10.4028/p-9EfKbt.

[8] R. C. Germanicus, T. Phulpin, K. Niskanen, A. Michez, and U. Lüders, “AFM-sMIM Characterization of the Recombination-Enhancing Buffer Layer for Bipolar Degradation Free SiC MOSFETs,” Solid State Phenomena, vol. 361, pp. 85–91, 2024, doi: 10.4028/p-hUPMo0.