Miniatu... Capacitors with Ultrathin Ta$_2$O$_5$ Films Prepared by Atomic Layer Deposition

Denise Molinnus, Heiko Iken, Anna Lynn Johnen, Benjamin Richstein, Lena Hellmich, Arshak Poghossian, Joachim Knoch, and Michael J. Schöning*
disadvantages as well as the need to reduce the insulator's tunneling gate leakage current. This is realized by increasing the physical thickness of the gate insulator and at the same time decreasing the equivalent oxide thickness (EOT; note that EOT of single or stacked gate insulators is defined as the thickness of SiO₂ that would provide the same accumulation capacitance) by increasing the permittivity of the gate insulator.⁴⁷,⁴⁸ A decrease of the EOT via high-κ gate insulators results in an enhancement of both the effectiveness of capacitive coupling and sensitivity (steepness of the slope) of the capacitance–voltage curve in the depletion region with respect to interfacial potential changes, e.g., induced by pH changes or molecular interactions on the gate surface.⁴⁹ In addition, increasing the gate capacitance per surface area may also reduce the impact of possible parasitic capacitances (input capacitance of the measurement equipment, cables, etc.) and enhances the signal-to-noise ratio, especially in the case of EISCAPs with a very small sensing area.

Among different high-κ dielectrics utilized in pH-sensitive field-effect devices, amorphous Ta₂O₅ films have been recognized as one of the best pH-sensitive materials,⁵⁰ having a large surface buffer capacity, high refractive index (≈2.2), relatively wide bandgap (≥4.3 eV), high dielectric constant (22–28), low leakage current, and good dielectric breakdown strength.⁵¹ Moreover, in addition to the high pH-sensitive behavior, Ta₂O₅ films possess corrosion-resistant properties, making them very attractive for the application in cleaning-in-place or sterilize-in-place, suitable for corrosion-resistant properties, making them very attractive for the application in cleaning-in-place or sterilize-in-place, suitable for sterilization purposes. The excellent ability to act as a diffusion barrier, Si₃N₄ layers grown by atomic layer deposition (ALD) due to its excellent ability to act as a diffusion barrier, Si₃N₄ layers grown by atomic layer deposition (ALD).

2.2. Preparation of EISCAP Chips

Three types of EISCAP structures consisting of Al–p-Si–Ta₂O₅, Al–p-Si–Si₃N₄–Ta₂O₅, and Al–p-Si–SiO₂–Ta₂O₅ were prepared. Figure 1 shows the fabrication process steps of the EISCAPs with different layer stacks. The ultrathin Ta₂O₅ layer was grown directly on a cleaned Si substrate (layer system (i)) or on a nitridated layer system (iii) and an oxidized layer system (iii) Si, respectively. The Si₃N₄ layers were grown by RTN for 60 s (2000 sccm NH₃) at 750 and 950 °C, resulting in 1 and 2 nm ultrathin Si₃N₄ films, respectively.⁵³ For the preparation of the SiO₂ layer, the Si substrate was subject to rapid thermal oxidation (RTO) for 16 s at 1050 °C (2000 sccm O₂), resulting in a 3.6 nm SiO₂ thin film.

The Ta₂O₅ layer was grown by ALD technique (FlexAl, Oxford Plasma Technology) with the precursor tris-(diethylamido)-( tert-butylimidido)tantalum⁵⁶ by a growth rate of 0.08 nm/cycle at a substrate temperature of 200 °C, assisted by O₂ plasma (300 W) to obtain the final Ta₂O₅ surface layer. Sixty cycles were performed to get a 5 nm-thick Ta₂O₅ layer. The thicknesses of the Si₃N₄, SiO₂, and Ta₂O₅ layers were confirmed by ellipsometric measurements (Ellipsometer, Accurion, GmbH, Germany).

As a rear-side contact, a 300 nm-thick aluminum layer was deposited by electron-beam evaporation with a deposition rate of 0.5 nm s⁻¹, followed by a rapid thermal annealing process for 10 min at 400 °C under N₂ atmosphere. Before electron-beam deposition, the surplus SiO₂ or Si₃N₄ on the rear side of the wafer that is grown during the previous RTN and RTO processes is removed (short hydrofluoric acid dip). The next step included the dicing of the wafer into 1 cm × 1 cm chips. For the miniaturized EISCAPs, a 1.25 μm-thick SU-8 photoresist was spin-coated onto the chips (serving as an additional passivation layer) and patterned to achieve electrolyte reservoirs with a sensing area of ≈0.8 mm². Note that the sensing area of the EISCAPs presented in this study is noticeably smaller than that of reported in previous studies (from 1.7 up to 50 mm²; see, e.g., refs.[26,34,57-59]).

2.3. Implementation of Measurements

To carry out different electrochemical measurements, the EISCAP sensors were mounted into a homemade measuring cell, sealed by an O-ring to protect the chip sidewalls and the rear-side contact from the solution. Figure 2 (left) depicts the measurement setup used for the characterization of the EISCAPs.

The EISCAP sensors with the different stack compositions of i) p-Si–Ta₂O₅; ii) p-Si–Si₃N₄–Ta₂O₅; and iii) p-Si–SiO₂–Ta₂O₅ were characterized in Titrisol buffer solution of different pH values between pH 4 and pH 9 by means of C–V (capacitance–voltage) and ConCap (constant–capacitance)
method using an impedance analyzer (Zennium, Zahner Elektrik, Germany). Furthermore, as the gate leakage-current level is a critical indicator for a correct operation of EISCAPs, before C–V and ConCap measurements, the leakage current was proven in a pH 7 buffer at applied gate voltages from \(-2\) to \(1.5\) V. The pH value of the buffer solutions was controlled with a pH meter (Mettler-Toledo, Germany).

For the implementation of C–V measurements, a sweeping direct current (DC) gate voltage \((V_G)\) ranging from \(-2\) to \(1.5\) V (100 mV steps) and a small alternating current (AC) voltage \((V_{AC})\) of 20 mV with a frequency of 190 Hz was applied between the Ag/AgCl reference electrode and the rear-side Al contact. Additionally, ConCap measurements were performed to allow the monitoring of the real-time dynamic sensor signal, at which the capacitance of the sensor is kept constant at a working point \((C_{WP})\), chosen from the depletion region of the C–V curve. Measurements were performed at room temperature in a dark Faraday cage. For each EISCAP type, three sensors were tested. After mounting the sensor into the measuring cell and sealing by an O-ring, the sensor was conditioned in Titrisol buffer solution of pH 7 for 24 h before starting the measurements. To study the long-term behavior, the EISCAPs with Ta2O5, Si3N4–Ta2O5 and SiO2–Ta2O5 gate insulators were periodically characterized over a time period of up to 71 days. When not in use, the sensors installed in the measurement chambers were stored in Titrisol buffer of pH 7.

![Fabrication process steps of the EISCAPs with different layer stacks: i) p-Si–Ta2O5, ii) p-Si–Si3N4–Ta2O5, and iii) p-Si–SiO2–Ta2O5. RTN, rapid thermal nitridation; RTO, rapid thermal oxidation.](image1)

![Figure 1. Fabrication process steps of the EISCAPs with different layer stacks: i) p-Si–Ta2O5, ii) p-Si–Si3N4–Ta2O5, and iii) p-Si–SiO2–Ta2O5. RTN, rapid thermal nitridation; RTO, rapid thermal oxidation.](image2)
2.4. Equivalent Circuit of EISCAP Chip with Sensing and Non-Sensing Regions

The sensing area ($A_s$) of the EISCAP chip surface with the solution is defined by the patterned SU-8 layer (electrolytic reservoir with direct contact to the pH-sensitive $Ta_2O_5$, while the contact area ($A_c$) of the EISCAP chip surface with the solution is given by the inner diameter of the O-ring. Figure 2 (right) illustrates the simplified electrical equivalent circuit of the EISCAP chip combining the sensing region and the non-sensing region covered with the 1.25 $\mu$m-thick SU-8 layer.

The equivalent capacitance of the EISCAP chip ($C_{eq}$) is determined as

$$C_{eq} = C_s + C_{non-s}$$

where $C_s$ and $C_{non-s}$ are the overall capacitances of the sensing and non-sensing region. The overall capacitance of the sensing region, $C_s$, is determined by the combination of the gate insulator ($C_\text{g}$) and space charge ($C_{ssc}$) capacitances in series

$$C_s = \frac{C_\text{g} C_{ssc}}{C_\text{g} + C_{ssc}}$$

where $C_{ssc}$ is the capacitance of the undeformed depletion region (Figure 3a);

$$\frac{1}{C_{non-s}} = \frac{1}{C_{SU-8}} + \frac{1}{C_i} + \frac{1}{C_{sc}}$$

with $C_i = A_{non-s} C_{Ta2O5}, C_i = A_{non-s} C_{Si3N4} C_{Ta2O5}/(C_{Si3N4} + C_{Ta2O5}),$ and $C_{ssc} = A_{non-s} C_{SiO2} C_{Ta2O5}/(C_{SiO2} + C_{Ta2O5})$ for the gate insulator system of $Ta_2O_5, Si_3N_4,$ and $SiO_2$. The total capacitance depends on the gate voltage or surface potential changes induced by the pH change. The gate leakage current at different pH values are presented in Figure 3b. As can be seen, the ConCap curves drift with different pH values are presented in Figure 3b. As can be seen, even after a storage time of 22 days, the EISCAP immediately responds to pH changes with a clear pH dependence of the gate stack and limits the EOT. However, in spite of deformed C-V curves, they have no impact on the basic sensor results achieved in this study because the working point for further characterization of pH-sensitive properties of ALD-deposited $Ta_2O_5$-gate EISCAPs was chosen in the quasilinear range of the undeformed depletion region (Figure 3a); $C_{wp} = 18$ nF. Here, the total capacitance depends on the gate voltage or surface potential changes induced by the pH change. The gate leakage current at the working point ($C_{wp}$) was evaluated from the respective I-V plot (not shown) and amounts to be 2 nA.

3. Results and Discussion

3.1. Electrochemical Characterization of p-Si–$Ta_2O_5$ EISCAP Chips

C–V measurement is one of the most convenient methods to characterize capacitive field-effect sensors such as EISCAPs. Figure 3a shows representative high-frequency C–V curves of the p-Si–$Ta_2O_5$ EISCAP system recorded in pH 7 buffer after storing for 1 (blue line), 8 (red line), and 22 days (green line), respectively. As can be seen, the C–V curves in the depletion region are deformed: a plateau-like course is visible in the depletion region at a gate voltage between approximately $-0.4$ and $0.4$ V. A similar phenomenon has been observed in C–V curves of p-Si–SiO$_2$ EISCAPs after oxygen-plasma treatment of the SiO$_2$ surface, which might be attributed to plasma-induced slow states associated with trapped positive charges in the oxide. Another possible explanation for this behavior could be the formation of an uncontrolled interfacial SiO$_2$ layer (between the HF-treated Si substrate and $Ta_2O_5$) with a large interface density. The formation of such an interfacial layer has been evidenced during the direct deposition or post-annealing of many high-$\kappa$ materials on Si, including $Ta_2O_5$ films. It should be noted that this issue is one of the most serious challenges when replacing SiO$_2$ as gate insulator by high-$\kappa$ oxides. The presence of an additional low-$\kappa$ SiO$_2$ interfacial layer decreases the effective dielectric constant of the gate stack and limits the EOT.

The results of the ConCap measurements in buffer solutions with different pH values are presented in Figure 3b. As can be seen, even after a storage time of 22 days, the EISCAP immediately responds to pH changes with a clear pH dependence of the signal. With increasing storage time, the ConCap curves drift in the direction of smaller positive voltages. To investigate the hysteresis effect of the $Ta_2O_5$-gate EISCAPs, measurements in various pH buffer solutions were performed in the following sequence of steps: pH 7-6-5-4-5-6-7-8-9-8-7. The hysteresis of the EISCAP was defined as the difference between the ConCap signals recorded in same pH buffer by downward and upward series of pH measurements and amounted to be $\pm 2$ mV at pH 7.

The calibration curves of the sensor evaluated from the ConCap responses are depicted in Figure 3c. The $Ta_2O_5$-gate EISCAP confirms a linear calibration behavior with a nearly Nernstian pH sensitivity of $55.1 \pm 0.76$ mV pH$^{-1}$. Due to the sensor drift over time (which is typical for field-effect sensors), the calibration curves were shifted parallel along the voltage axis. Therefore, similar to conventional pH- or ion-selective electrodes, a periodic calibration of EISCAPs is needed.

Figure 3d demonstrates the long-term stability of the $Ta_2O_5$-gate EISCAP. The pH sensitivity was practically constant for at least 22 days storage in buffer. The blue dashed line represents...
the drift of the ConCap signal at pH 7 over time. The evaluated long-term drift rate was about 2.2 mV day\(^{-1}\) or 0.04 pH day\(^{-1}\) (taking into account a pH sensitivity value of 55.1 mV pH\(^{-1}\)).

3.2. Electrochemical Characterization of p-Si\(_{-}\)Si\(_3\)N\(_4\)–Ta\(_2\)O\(_5\) EISCAP Chips

The p-Si–Si\(_3\)N\(_4\)–Ta\(_2\)O\(_5\) EISCAP chips with different Si\(_3\)N\(_4\) thicknesses of \(\approx 1\) and \(\approx 2\) nm were periodically characterized in terms of pH sensitivity, hysteresis, and drift over a time period of 21–23 days. Figure 4a depicts exemplarily C–V plots of these sensors measured in pH 7 buffer after 1 day (for EISCAP with 1 nm Si\(_3\)N\(_4\)) and 8 days (for EISCAP with 2 nm Si\(_3\)N\(_4\)) storage in buffer solution. Due to different thicknesses of the Si\(_3\)N\(_4\) layer in the Si\(_3\)N\(_4\)–Ta\(_2\)O\(_5\) stack and, therefore, different EOT values, the C–V curves are shifted along both the capacitance and the voltage axis. As expected, the slope of the C–V curve of the EISCAP with a 1 nm Si\(_3\)N\(_4\) layer is steeper than that of the EISCAP with 2 nm Si\(_3\)N\(_4\). The C–V curves of both EISCAPs are slightly deformed in the depletion region; however, the plateau-like behavior is less pronounced in comparison to that of the p-Si–Ta\(_2\)O\(_5\) sensors. This can be attributed to a substantially reduced density of interface states achieved with the RTN growth process compared to the p-Si–Ta\(_2\)O\(_5\) EISCAPs discussed in the previous section.

The working points for ConCap measurements were chosen in the undeformed depletion region at \(C_{WP} = 24 \text{ nF}\) and \(C_{WP} = 15 \text{ nF}\). The leakage current at these working points was 6.5 and 5.5 nA, respectively. The ConCap signals of both EISCAPs measured in the loop of pH 7-6-5-5-6-7-8-9-8-7 show identical behavior with a clear pH dependence and a relatively small hysteresis of 2.7 and 3.2 mV for the EISCAPs with a 1 and 2 nm Si\(_3\)N\(_4\) layer, respectively (see Figure 4b). The pH sensitivity values evaluated from the linear calibration curves shown in Figure 4c were very similar with \(54.8 \pm 0.27\) and \(54.6 \pm 0.51 \text{ mV pH}^{-1}\) for the sensor with 1 and 2 nm Si\(_3\)N\(_4\), respectively. They remain constant during the tested time period of 3 weeks (see Figure 4d). The evaluated rates for long-term drift were about 2.5 mV day\(^{-1}\) (or 0.05 pH day\(^{-1}\)) and 1.8 mV day\(^{-1}\) (or 0.03 pH day\(^{-1}\)) for the EISCAPs with 1 and 2 nm Si\(_3\)N\(_4\).

3.3. Electrochemical Characterization of p-Si–SiO\(_2\)–Ta\(_2\)O\(_5\) EISCAP Chips

The EISCAPs with the SiO\(_2\)–Ta\(_2\)O\(_5\) gate insulator stack were periodically characterized over a time period of 71 days.

Figure 3. Characteristics of p-Si–Ta\(_2\)O\(_5\) EISCAP pH sensors over time: a) C–V curves; b) ConCap responses; c) calibration curves; d) pH sensitivity and ConCap signal drift over time.
Representative high-frequency $C-V$ plots of the p-Si–SiO$_2$–Ta$_2$O$_5$ EISCAP chips recorded in pH 7 buffer after 1 day and 71 days of storage are presented in Figure 5a. In contrast to the EISCAPs with Ta$_2$O$_5$ and Si$_3$N$_4$–Ta$_2$O$_5$ gate insulators, the SiO$_2$–Ta$_2$O$_5$-gate EISCAPs show undeformed (regular) $C-V$ curves with clearly defined accumulation, depletion, and inversion regions. With increasing operation time, the $C-V$ curve is shifted along both the capacitance and the voltage axis. As the Ta$_2$O$_5$ layer was not damaged, the possible reason for this increase of accumulation capacitance with longer storage time could be the rise of the sensing area due to the penetration of electrolyte underneath the SU-8 passivation layer. At the same time, the shift of the $C-V$ curve along the voltage axis is most likely associated with the long-term drift of the EISCAP signal.

The ConCap response of the SiO$_2$–Ta$_2$O$_5$-gate EISCAP was recorded at a working point of $C_{WP} = 6$ nF. The leakage current at this working point was 0.3 nA. Even after a long storage period of 71 days, the ConCap signal drift at pH 7 over time (see Figure 5d), and amounted to be $\approx 2$ mV day$^{-1}$ (or 0.04 pH day$^{-1}$).

### 3.4. Comparison of Characteristics of EISCAP Sensor Chips with Gate Insulators of Ta$_2$O$_5$, Si$_3$N$_4$–Ta$_2$O$_5$, and SiO$_2$–Ta$_2$O$_5$

The SiO$_2$–Ta$_2$O$_5$-gate EISCAP offers linear calibration curves over the overall measurement period of at least 71 days. The calibration curves are shifted in parallel along the potential axis due to the long-term drift of the EISCAP sensor. The average pH sensitivity of the p-Si–SiO$_2$–Ta$_2$O$_5$ EISCAP chip evaluated from the respective calibration plots was $56.2 \pm 0.76$ mV pH$^{-1}$ and remains (practically) constant, at least over the studied time period (see Figure 5d). The long-term drift rate was evaluated from the ConCap signal drift at pH 7 over time (see Figure 5d), and amounted to be $\approx 2$ mV day$^{-1}$ (or 0.04 pH day$^{-1}$).
than those of previously reported ALD-prepared (52.8 mV pH⁻¹)[2] and e-beam evaporated (51.4 mV pH⁻¹)[57] Ta₂O₅ films, and are in good agreement with the pH sensitivity (56.2 mV pH⁻¹) of Ta₂O₅ layers prepared by thermal oxidation of sputtered Ta[34] and slightly lower than values from our group achieved for Ta₂O₅ films fabricated via thermal oxidation of electron-beam evaporated Ta (58 mV pH⁻¹).[58]

Generally, better sensor characteristics in terms of high sensitivity, small long-term drift, and low hysteresis have been obtained for EISCAPs with a SiO₂–Ta₂O₅ stacked gate insulator system. Moreover, these sensors also have the lowest leakage current. Note that a large leakage current might lead to a serious deformation of the C–V curves or experimental artifacts and even electrolysis, depending on the potentials applied to the gate and the electrolyte concentration.

With regard to a simple sensor chip miniaturization, the capacitance of the p-Si–Ta₂O₅ system shows an about 5 times larger capacitance value at −2 V in comparison to the p-Si–SiO₂–Ta₂O₅ system. However, the capacitor also reveals a rather large interface state density giving rise to the plateau between approximately −0.4 and 0.4 V in the C–V curves. The p-Si–Si₃N₄–Ta₂O₅ system with 1 nm Si₃N₄, on the other hand, shows a substantially lower interface density of states and a capacitance value almost as good as for the p-Si–Ta₂O₅ system, i.e., substantially larger than the p-Si–SiO₂–Ta₂O₅ reference. As a result, a larger working point CWP (about 4 times higher than for the p-Si–SiO₂–Ta₂O₅ system) can be chosen which is important

Figure 5. Characteristics of p-Si–SiO₂–Ta₂O₅ EISCAP pH sensors: a) C–V curves; b) ConCap responses; c) calibration curves; d) pH sensitivity and ConCap signal drift over time.

Table 1. Basic characteristics of EISCAP pH sensors with different stack compositions.

| Gate insulator | Sensitivity, Long-term drift, Hysteresis, Leakage current at working point, Maximum leakage current in range −2 to 1.5 V, [nA] |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ta₂O₅ (5 nm)   | 55.1 ± 0.8, 2.2 ± 0.04, 2.2 ± 0.7, 2.0, 15                                                                                     | 54.8 ± 0.3, 2.5 ± 0.05, 2.7 ± 0.8, 6.5, 9                                                                                   |
| Si₃N₄ (1 nm)– Ta₂O₅ (5 nm) | 54.6 ± 0.5, 1.8 ± 0.03, 3.2 ± 0.9, 5.5, 6                                                                                     | 56.2 ± 0.8, 2.0 ± 0.04, 1.0 ± 0.6, 0.3, 2                                                                                   |
| SiO₂ (3.6 nm)– Ta₂O₅ (5 nm) | 56.2 ± 0.8, 2.0 ± 0.04, 1.0 ± 0.6, 0.3, 2                                                                                      | 56.2 ± 0.8, 2.0 ± 0.04, 1.0 ± 0.6, 0.3, 2                                                                                   |
particularly for miniaturized EISCAPs. In addition, due to the lower equivalent oxide thickness, the EISCAPs with the Si$_3$N$_4$(1 nm)–Ta$_2$O$_5$ stack offer a higher steepness in the slope of the capacitance–voltage curve.

4. Conclusions

Three different EISCAPs of Al–p-Si–Ta$_2$O$_5$(5 nm), Al–p-Si–Si$_3$N$_4$(1 or 2 nm)–Ta$_2$O$_5$ (5 nm), and Al–p-Si–SiO$_2$(3.6 nm)–Ta$_2$O$_5$(5 nm) with ultrathin gate insulator layers have been studied and systematically compared in terms of their pH-sensitive behavior. Such ultrathin gate insulator stacks were applied for the first time for pH-sensitive EISCAPs demonstrating good sensor performance, originated from the 5 nm-thick ALD-prepared Ta$_2$O$_5$ layer, which serves as pH-sensitive transducer layer. For the electrochemical sensor characterization, C–V, ConCap as well as leakage current measurements were performed in buffer solutions between pH 4 and pH 9. All EISCAPs showed defined pH responses with clear signal behavior, independently of increasing or decreasing pH direction, having a nearly Nernstian sensitivity with 54.6–56.2 mV pH$^{-1}$. Long-term drift and hysteresis are in good agreement with the literature data for similar material compositions; however, in that case the insulator thickness is typically at least 10 times higher. When focusing on the overall sensor characteristics, the stacked gate insulator of SiO$_2$–Ta$_2$O$_5$ is favored, while the Si$_3$N$_4$(1 nm)–Ta$_2$O$_5$ stack delivers a higher steepness in the slope of the C–V curve due to the lower equivalent oxide thickness.

The main benefit of all three types of EISCAPs in this experiment was the miniaturization of the active sensor area to 0.8 mm$^2$. At the same time, the geometry we selected as a first “proof-of-concept,” which allows even further size reduction by utilizing these ultrathin gate insulators.

In future studies, we will focus on the functionalization of the miniaturized field-effect capacitors with ion-sensitive membranes$^{[62]}$ or enzymes.$^{[14]}$ Lateral miniaturization might enable to applying nanospotting of enzyme layers$^{[63]}$ to further increase the grade of automation. Here, the implementation of the miniaturized field-effect capacitor into microfluidic setups$^{[59]}$ opens the opportunity for complete lab-on-chip applications.

Acknowledgements

The authors would like to thank M. Geitner and A. Trajcev for their assistance in ALD layer preparation. This work was, in part, supported by Deutsche Forschungsgemeinschaft under grants KN545/24-1 and KN545/29-1. Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

atomic layer deposition, capacitive field-effect sensors, pH sensors, Ta$_2$O$_5$, ultrathin gate insulators

Received: September 30, 2021
Revised: December 21, 2021
Published online: February 3, 2022

[1] M. J. Schöning, D. Brinkmann, D. Rolka, C. Demuth, A. Poghossian, Sens. Actuators, B 2005, 111–112, 423.
[2] S. Mross, T. Zimmermann, N. Winkin, M. Kraft, H. Vogt, Sens. Actuator B Chem. 2016, 236, 937.
[3] H. Cho, K. Kim, M. Meyyappan, C.-K. Baek, Sens. Actuators, B 2019, 279, 183.
[4] H. Barhoumi, R. Haddad, A. Maaref, J. Bausells, F. Bessuelle, D. Léonard, N. Jaffrezic-Renault, C. Martelet, N. Zine, A. Errachid, Sens. Lett. 2008, 6, 204.
[5] G. Z. Gafyfallou, L. C. de Smet, E. J. Sudhölter, Sens. Actuators, B 2012, 168, 207.
[6] Y.-T. Lin, J.-D. Luo, C.-C. Chiou, C.-M. Yang, C.-Y. Wang, C. Chou, C.-S. Lai, Sens. Actuators, B 2013, 186, 374.
[7] A. Poghossian, M. Jablonski, C. Koch, T. S. Bronder, D. Rolka, C. Wege, M. J. Schöning, Biosens. Bioelectron. 2018, 110, 168.
[8] M. Jablonski, A. Poghossian, M. Keusgen, C. Wege, M. J. Schöning, Anal. Bioanal. Chem. 2021, 413, 5669.
[9] A. Poghossian, M. Bäcker, D. Mayer, M. J. Schöning, NanoScale 2015, 7, 1023.
[10] N. Kumar, S. Kumar, J. Kumar, S. Panda, J. Electrochem. Soc. 2017, 164, B409.
[11] R. Chand, D. Han, S. Neethirajan, Y.-S. Kim, Sens. Actuators, B 2017, 248, 973.
[12] D. A. Oliveira, D. Molinnus, S. Beging, J. R. Siqueira, M. J. Schöning, Phys. Status Solidi A 2021, 218, 2000747.
[13] J. R. Siqueira, D. Molinnus, S. Beging, M. J. Schöning, Anal. Chem. 2014, 86, 5370.
[14] D. Molinnus, L. Muschalik, L. O. Gonzalez, J. Bongaerts, T. Wagner, T. Selmer, P. Siegent, M. Keusgen, M. J. Schöning, Biosens. Bioelectron. 2018, 115, 1.
[15] A. Poghossian, M. Thust, P. Schroth, A. Steffen, H. Lüth, M. J. Schöning, Sens. Mat. 2001, 4, 207.
[16] A. Poghossian, K. Malzahn, M. H. Abouzar, P. Mehndiratta, E. Katz, M. J. Schöning, Electrochim. Acta 2011, 56, 9661.
[17] E. Katz, A. Poghossian, M. J. Schöning, Anal. Bioanal. Chem. 2017, 409, 81.
[18] D. Molinnus, A. Poghossian, M. Keusgen, E. Katz, M. J. Schöning, Electroanalysis 2017, 29, 1840.
[19] A. Poghossian, M. J. Schöning, Sensors 2020, 20, 5639.
[20] L. Mu, Y. Chang, S. D. Sawtelle, M. Wipf, X. Duan, M. A. Reed, IEEE Access 2015, 3, 287.
[21] S. A. Pullano, C. D. Critello, I. Mahibub, N. T. Tasneem, S. Shamsir, S. K. Islam, M. Greco, A. S. Fiorillo, Sensors 2018, 18, 4042.
[22] Y.-C. Syu, W.-E. Hsu, C.-T. Lin, ECS J. Solid State Sci. Technol. 2018, 7, Q3196.
[23] A. Poghossian, M. Jablonski, D. Molinnus, C. Wege, M. J. Schöning, Front. Plant Sci. 2020, 11, 598103.
[24] A. Poghossian, M. J. Schöning, Curr. Opin. Electrochem. 2021, 29, 100811.
[25] C. Wu, A. Poghossian, T. S. Bronder, M. J. Schöning, Sens. Actuators, B 2016, 229, 506.
[26] S. Dastidar, A. Agarwal, N. Kumar, V. Bal, S. Panda, IEEE Sens. J. 2015, 15, 2039.
[27] T. N. Lee, H. J. H. Chen, Y.-C. Huang, K.-C. Hsieh, J. Electrochem. Soc. 2018, 165, B767.
[28] T. Yoshinobu, H. Ecken, A. Poghossian, H. Lüth, I. Waseki, M. J. Schöning, Sens. Actuators, B 2001, 66, 388.
[29] C.-S. Lai, C.-E. Lue, C.-M. Yang, D. G. Pijanowska, J. Electrochem. Soc. 2010, 157, 18.
[30] H.-J. Jang, M.-S. Kim, W.-J. Cho, IEEE Electron Device Lett. 2011, 32, 171–172.
[31] J. L. Chang, Y. Lee, C. Lai, H. Ko, L. Hsieh, B. Veigas, R. Branquinho, J. V. Pinto, P. J. Wojcik, R. Martins, C.-S. Lai, C.-E. Lue, C.-M. Yang, D. G. Pijanowska, T. Yoshinobu, H. Ecken, A. Poghossian, H. Lüth, H. Iwasaki, T. N. Lee, H. J. H. Chen, Y.-C. Huang, K.-C. Hsieh, www.advancedsciencenews.com
[32] M. Chen, Y. Jin, X. Qu, Q. Jin, J. Zhao, Sens. Actuators, B 2014, 192, 399.
[33] B. Veiga, R. Branquinho, J. V. Pinto, P. J. Wojcik, R. Martins, E. Fortunato, P. V. Baptista, Biosens. Bioelectron. 2014, 52, 50.
[34] J. L. Chang, Y. Lee, C. Lai, H. Ko, L. Hsieh, ECS Trans. 2006, 2, 1.
[35] K.-M. Chang, K.-Y. Chao, T.-W. Chou, C.-T. Chang, Jpn. J. Appl. Phys. 2007, 46, 4333.
[36] C.-M. Yang, C.-S. Lai, T.-F. Lu, T.-C. Wang, D. G. Pijanowska, J. Electrochem. Soc. 2008, 155, J326.
[37] T.-F. Lu, H.-C. Chuang, J.-C. Wang, C.-M. Yang, P.-C. Kuo, C.-S. Lai, Jpn. J. Appl. Phys. 2011, 50, 10PG03.
[38] Z. Fredj, A. Baraket, M. Ben Ali, N. Zine, M. Zabala, J. Bausells, A. Elaissari, N. U. Benson, N. Jaffrezic-Renault, A. Errachid, Chemosensors 2021, 9, 13.
[39] C. H. Kao, H. Chen, M. L. Lee, C. C. Liu, H.-Y. Ueng, Y. C. Chu, C. B. Chen, K. M. Chang, Sens. Actuators, B 2014, 194, 503.
[40] P.-K. Shin, Appl. Surf. Sci. 2003, 214, 214.
[41] J. C. Chou, Y. F. Wang, Sens. Actuators, B 2002, 86, 58.
[42] C.-M. Yang, C.-Y. Wang, C.-S. Lai, J. Vac. Sci. Technol. 2014, 32, 03D113.
[43] V. V. Buniatyan, M. H. Abouzar, N. W. Martirosyan, J. Schubert, S. Gevorgian, M. J. Schöning, A. Poghossian, Phys. Status Solidi A 2010, 207, 824.
[44] C.-H. Kao, W. T. Chiu, Y. C. Chen, L. Yang, S. C. Tsai, T. W. Chang, C.-T. Tsai, C.-Y. Lin, H. Chen, Vacuum 2017, 140, 3.
[45] L. Colombo, J. Chambers, H. H. Niimi, Electrochem. Soc. Interface 2007, 16, 51.
[46] S. van Elshocht, C. Adelmann, P. Lehnen, S. de Gendt, Electrochem. Soc. Interface 2007, 16, 51.
[47] A. Poghossian, R. Welden, V. V. Buniatyan, M. J. Schöning, Sensors 2021, 21, 6161.
[48] T. Henke, M. Knaut, M. Geidel, F. Winkler, M. Albert, J. W. Bartha, Thin Solid Films 2017, 627, 94.
[49] M. Bäcker, S. Beging, M. Biselli, A. Poghossian, J. Wang, W. Zang, P. Wagner, M. J. Schöning, Electrochim. Acta 2009, 54, 6107.
[50] T. Mikolajick, R. Kühnhold, H. Ryssel, Sens. Actuators, B 1997, 44, 262.
[51] C.-E. Lue, T.-C. Yu, C.-M. Yang, D. G. Pijanowska, C.-S. Lai, Sensors 2011, 11, 4562.
[52] A. P. Huang, P. K. Chu, Surf. Coat. Technol. 2005, 200, 1714.
[53] S. Fischer, H. I. Kremer, B. T. T. BerghoffMaßMaß, T. Maß, T. Taubner, J. Knoch, Phys. Status Solidi A 2016, 213, 1494.
[54] X. Yuan, N. Wolf, T. J. J. Hondrich, P. Shokoohimehr, F. Milos, M. Glass, D. Mayer, V. Maybeck, M. Prömpers, A. Offenhäusser, R. Wördenweber, ACS Appl. Mater. Inter. 2020, 12, 17121.
[55] N. Kumar, A. P. Tiwari, J. Kumar, S. Panda, in: 2015 2nd Inter. Symp. on Physics and Technology of Sensors (IPTTS), IEEE, Pune, India, July–October 2015, pp. 214–218.
[56] M. Jablonski, A. Poghossian, R. Severins, M. Keusgen, C. Wege, M. J. Schöning, Micromachines 2021, 12, 57.
[57] M. J. Schöning, N. Näther, V. Auger, A. Poghossian, M. Koudelka-Hep, Sens. Actuators, B 2005, 108, 986.
[58] J. Gun, V. Gutkin, O. Lev, H.-G. Boyen, M. Saitner, P. Wagner, M. D’Olieslaeger, M. H. Abouzar, A. Poghossian, M. J. Schöning, J. Phys. Chem. C 2011, 115, 4439.
[59] A. Paskaleva, E. Atanassova, Solid-State Electron. 1998, 42, 777.
[60] Y. Mourzina, M. J. Schöning, J. Schubert, W. Zander, A. Legin, Y. Vlasov, P. Kordos, H. Lüth, Sens. Actuators, B 2000, 71, 13.
[61] D. Molinnus, S. Beging, C. Lowis, M. J. Schöning, Sensors 2020, 20, 4924.