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Highly Sensitive Detection of Urinary Cadmium to Assess Personal Exposure

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Abstract

A series of Boron-Doped Diamond (BDD) ultramicroelectrode arrays were fabricated and investigated for their performance as electrochemical sensors to detect trace level metals such as cadmium. The steady-state diffusion behavior of these sensors was validated using cyclic voltammetry followed by electrochemical detection of cadmium in water and in human urine to demonstrate high sensitivity ($>200 \mu\text{A/ppb/cm}^2$) and low background current ($<4 \text{ nA}$). When an array of ultramicroelectrodes was positioned with optimal spacing, these BDD sensors showed a sigmoidal diffusion behavior. They also demonstrated high accuracy with linear dose dependence for quantification of cadmium in a certified reference river water sample from the National Institute of Standards and Technology (NIST) as well as in a human urine sample spiked with 0.25–1 ppb cadmium.

Keywords

Boron-Doped Diamond (BDD); ultramicroelectrode array; electrochemical sensors; urinary trace metal detection; cadmium; differential pulse stripping voltammetry (DPSV)

1. Introduction

Cadmium is considered a highly toxic heavy metal, even at trace levels, and extended environmental exposure to cadmium can cause serious health issues such as nephrotoxicity, bone demineralization, and cancer[1, 2]. With a long metabolic half-life, cadmium tends to bioaccumulate in humans, and its accurate assessment in biological samples at low parts-per-billion (ppb) levels can be used to monitor personal exposure. The determination of cadmium levels in human urine is especially useful to indicate an individual's total body burden and likelihood for toxic effects [1]. Electrochemical sensors for detection of toxic metals and substances have received much attention due to their ease of use for field analysis, low limit of detection (LOD) values, and ability to analyze complex sample matrices[3]. They provide rapid and reliable response without the need for complicated sample preparation steps and specialized instrumentation such as atomic absorption

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spectroscopy (AAS), high performance liquid chromatography (HPLC), and inductively coupled plasma mass spectrometry (ICP-MS). Boron-Doped Diamond (BDD) electrodes are especially attractive due to their exceptional intrinsic properties compared to other carbon-based and noble metal electrodes. They possess a wide working potential window (approximately 3.4V) to enable analysis of a broad range of analytes and solutions, stable morphology and microstructure to survive harsh chemical environments, and low background currents to maximize signal-to-noise ratio[4]. These properties make BDD sensing electrodes excellent candidates to detect trace metals by allowing redox potentials outside the range of other electrodes, lessening side reactions caused by solvent breakdown, and preventing electrode fouling with long-term use. BDD electrodes have been especially useful for electrochemical detection of analytes in environments where the adsorption of organic molecules, pharmaceuticals, and other biomolecules such as proteins present a challenge for reliable sensor response [5–8].

Ultramicroelectrodes (UME) are a special class of electrodes with at least one dimension being smaller than 25 μm , called the critical dimension[9]. At sufficiently long times, this is smaller than or comparable to the thickness of the diffusion layer formed on the electrode surface, which results in a steady-state (limiting) current at the UME and the electrochemical reaction rate is maximized. Due to the enhancement of mass transport compared to the macro-scale electrodes, UMEs exhibit enhanced sensitivity compared to macroelectrodes even without normalization of the signal magnitude with respect to active area. As the geometric dimensions of a sensing electrode become progressively smaller, the diffusion profile of the analyte to the surface becomes hemispherical instead of planar, significantly enhancing mass transport[5, 10]. This results in reduction of non-Faradaic currents and improved kinetics at the electrode surface. However, the smaller size of the electrode also results in lower total detection current. To circumvent this issue, an array of electrodes can be formed where the individual UMEs are placed sufficiently far from one another to create an electrode with greater summed current, while still allowing for the enhanced diffusion behavior. This also provides higher current density with small capacitive-charging currents and better signal-to-noise ratio, thus improving accuracy, precision, and detection limits [11, 12]. Researchers have observed the enhanced sensitivity of UME arrays in several instances [13–16] and shown a variety of examples for electrochemical sensor applications such as the use of BDD arrays for glucose [17], dopamine[18], and metal[19] detection, as well as gold UME arrays for groundwater arsenic detection[20].

However, the reliable detection of metals at low parts-per-billion (ppb) level requires extremely sensitive electrodes with stable and reproducible sensitivity over time. Even with the use of BDD electrodes, it can be challenging to obtain reliable and reproducible responses, especially in the presence of interfering substances and complex organic matrices such as urine and blood [21, 22]. *To overcome the difficulties associated with the current electrochemical metal sensors and methods, here we report the fabrication and electrochemical characterization of two types of BDD UME arrays on silicon substrates followed by their utilization as highly sensitive electrochemical sensors to detect trace amounts of cadmium in water samples and in human urine.* To the best of our knowledge, this is the first demonstration of voltammetric detection of cadmium in urine at low sub-ppb levels, which is made possible by a unique combination of the use of BDD UME arrays and a highly refined differential pulse voltammetry algorithm to perform the cadmium detection in challenging detection media.

2. Experimental

2.1. Materials

For trace metal analysis, the use of ultrapure reagents is essential. All solutions were prepared with ultrapure deionized water twice purified using a Milli-Q Academic A10 Water Purification System (Millipore, >18.2 M Ω .cm resistivity at 25 °C). A cadmium standard (10.00 mg/mL in 4% HNO₃) was obtained from High Purity Standards. The cadmium stock solution was serially diluted to 0.1ppm which was used to make the standard additions. Acetate buffer was prepared from sodium acetate (99.995%, Sigma-Aldrich) and glacial acetic acid (99.99%, Sigma-Aldrich). NaOH solutions were prepared from sodium hydroxide monohydrate (99.9995%, Sigma-Aldrich); H₂SO₄ solutions were prepared from ultrapure H₂SO₄ (99.999%, Sigma-Aldrich). Glassware was cleaned with aqua regia using 3:1 ratio of HCl (99.999%, Sigma-Aldrich) and HNO₃ (99.99%, Sigma-Aldrich) and rinsing several times with ultrapure water.

2.2. Instrumentation

A 915 MHz microwave plasma assisted chemical vapor deposition reactor was used for polycrystalline diamond (PCD) thin film deposition. A second 2.45 GHz reactor was dedicated for BDD thin film deposition utilizing diborane as the boron-containing feed gas. Cyclic Voltammetry (CV) results were obtained using a CH Instruments 660C potentiostat. A PalmSens® (PalmSens, Utrecht, The Netherlands) handheld potentiostat and an HP iPAQ 214 Enterprise handheld computer were used to apply the detection algorithms and collect sensor data.

2.3 Fabrication and Characterization of BDD UME Arrays

The sensor design was based on a dual layer of electrically insulating (undoped) and conducting (boron doped) polycrystalline diamond, which were successively deposited on 75 mm silicon wafer substrates. An insulating silicon dioxide (SiO₂) layer was deposited followed by photolithographic processing steps to pattern the microarrays and expose the electroactive BDD area. An angled SEM image of a fully processed BDD UME is shown in Figure 2 along with the overlaying insulating SiO₂ layer. Roughness of the resulting BDD surfaces was measured using a Dektak 6M Stylus Profiler. Conductivity values were obtained using a Signatone 4-point probe stage and a probe including Hewlett-Packard (HP) readout components. Average thickness of the grown film was determined by weighing the wafer before and after diamond growth.

2.4. Cyclic Voltammetry (CV)

CV results were obtained by using a three electrode setup with BDD electrodes as the working, 3 mm Pt disc as the counter, and Ag/AgCl as the reference. The electrolyte solution consisted of 1 mM K₃Fe(CN)₆ or K₄Fe(CN)₆ with 1M KCl as the supporting electrolyte.

2.5. Differential Pulse Stripping Voltammetry (DPSV)

The applied electroanalytical technique to determine trace level cadmium was differential pulse stripping voltammetry (DPSV). All measurements were made in a 4ml glass cell with a custom made PTFE cap to hold the electrodes in place. The working electrode was a BDD UME array or a macroelectrode, counter electrode was a graphite rod (6 mm diameter, Sigma Aldrich), and the reference electrode was a KCl saturated leakless miniature Ag/AgCl (eDAQ, Inc.). DPSV parameters were optimized as following: The BDD electrodes were conditioned for up to 120 s at +1.2 V, cadmium was deposited for 300 s at -1.5 V, scan range -1.5 V to 0.2 V, potential step 5 mV, potential pulse 25 mV, pulse time 50 ms, scan

rate 50 mV/s. Stirring was applied during the conditioning and deposition steps and turned off for a 20 s equilibration time prior to the DPSV scan. 2–3 DPSV scans were taken at each concentration to ensure signal stability. Detection limits were calculated from $S/N = 3$, and the noise amplitude was determined from a flat portion of the blank DPSV scan[23].

2.6. Cadmium Detection in Water and Urine

Prior to cadmium detection, BDD electrodes were pre-treated by applying +3.5V to the electrode in 1M H₂SO₄ for 30 mins, the optimized anodic treatment procedure for detection of cadmium. It is widely accepted that BDD can be oxidized electrochemically by applying a sufficiently anodic potential[4]. This pre-treatment was only performed once per electrode to oxidize the BDD surface, changing the surface termination from hydrogen to oxygen. A certified reference material (SRM 1640a, Trace Elements in Natural Water) was obtained from the U.S. National Institute of Standards and Technology (NIST). This acidified water sample has certified levels of 22 trace metals including 3.992 ± 0.074 ppb Cd, 85.75 ± 0.51 ppb Cu, 12.101 ± 0.050 ppb Pb, and 55.64 ± 0.35 ppb Zn. For cadmium detection, a 2.5mL sample was taken of the NIST sample and was neutralized with NaOH and buffered to pH 4.0 with an acetate buffer (final solution concentration of 0.14M acetate buffer). Four BDD electrodes (two ultramicroelectrodes: MA-1, MA-2 and two macroelectrodes: LO and Elements Six) detected cadmium in the NIST sample using the DPSV parameters above with 60 s conditioning at +1.2V, 60 s deposition at -1.4V and a scan range of -1.4 to +0.4V.

Human urine was obtained from ProMedDx, LLC and was stored at -20°C until use. 1.5 ml urine was treated with an oxidation process by applying 200mA of current to two 1cm² BDD macro electrodes (Element Six) for 1 hr. The treated urine was diluted two-fold with 1.4mL ultrapure H₂O and 0.2mL 2M pH 4.0 acetate buffer (final acetate buffer concentration of 0.13M). Detection of cadmium was performed using the DPSV parameters above with 120 s conditioning and 300 s deposition at -1.5V.

3. Results & Discussion

The main goal of this study was to utilize an array of BDD ultramicroelectrodes separated by an insulating layer to maximize the overall sensor response and enhance the limit of detection (LOD) for trace metals such as cadmium. To investigate the performance enhancement of electrochemical sensors via the ultramicroelectrode effect, BDD sensing electrodes with various designs were developed and fabricated as shown in Figure 1. By judicious arrangement of UME arrays with controlled diameter and separations, it was possible to induce a hemispherical diffusion profile, and hence the desired ultramicroelectrode effect. Three different configurations of BDD electrodes were fabricated on silicon wafers and characterized for their physical, chemical, and electrochemical (sensing) characteristics. These included two generations of UME arrays (*MA-1* and *MA-2*) as well as an unpatterned control electrode with a large-area BDD opening (*LO*). Figure 1 schematically shows these BDD designs along with their actual dimensions and specifications. All three types of electrodes had a well-defined active BDD area to be exposed to the electrolyte solution, which was separated from the electrical contact pad via a SiO₂ insulating layer. The active area was unpatterned and fully exposed for the *LO* electrode whereas the *MA-1* and *MA-2* electrodes contained arrays of BDDs with center-to-center electrode UME separations of 60 μm and 120 μm, respectively. It is important to note that the *MA-2* sensor had a larger size to accommodate the larger UME separation. It also featured a hexagonal close packing arrangement for UMEs, maximizing the total active electrode area while keeping the UME separation constant. In the following sections, the fabrication of these sensing electrodes is described followed by evaluation of their performance as an electrochemical sensor to detect cadmium in water and human urine samples.

3.1. BDD Fabrication

The UME array fabrication consisted of two distinct processing sequences. The first sequence resulted in individual BDD sections that later formed the base for the contact pad, the middle insulator layer, and the active electrode area (Figure 1). The formed BDD sections became the substrate in the second processing sequence, in which a patterned SiO₂ insulating layer was applied on top of the BDD region to create the BDD contact pad and the array of BDD UMEs. The first fabrication sequence started with the growth of a dual composite layer of polycrystalline diamond (PCD) and BDD films on a 75 mm diameter silicon wafer. The resulting BDD surface had an average roughness of 25–40 nm with a sheet resistance of about 20 Ω/sq. measured by a 4-point probe setup. Since the dielectric PCD film was grown prior to the BDD film, the PCD and BDD films were grown in two different reactors to avoid boron contamination of the intrinsic dielectric PCD layer. The principle attributes of these reactors are described elsewhere[24]. Following the BDD growth, photolithographic masking was used to prepare this layer for plasma etching utilizing a microwave assisted electron cyclotron resonance etcher[25]. The final result was a group of electrically connected but spatially isolated BDD areas on the wafer.

The second processing sequence started with the deposition of an insulating SiO₂ layer covering the entire wafer by plasma enhanced chemical vapor deposition (PE-CVD). Following the SiO₂ deposition, another photolithographic processing step was applied using a different photo mask defining the contact pad and the array of UMEs. Subsequent to the photolithographic processing, the insulating SiO₂ layer was plasma etched to expose the active area. The fully processed wafer was finally laser cut into the individual sensors, hydrogen terminated in a plasma reactor, and vacuum sealed until use. An angled SEM image of a fully processed BDD UME is shown in Figure 2 along with the overlaying insulating SiO₂ layer.

3.2. BDD Characterization

Following the fabrication, individual BDD sensing electrodes were characterized with electron microscopy imaging, cyclic voltammetry (CV) using ferricyanide as the redox active probe, and measurements of surface roughness of the exposed diamond, film thickness, and electrical conductivity. Figure 3 shows the SEM micrographs of *MA-1* and *MA-2* electrodes showing the UME array configuration. While the UME center-to-center separation was accurate to the design, the actual UME sizes were slightly larger than the targeted diameter of 20 μm, possibly due to excessive etching during the masking/exposure steps involved in fabrication. All sensors resulted in consistent sheet resistance (~10–20 Ω/sq.) and surface roughness (40–60 nm) values as listed in Table 1. The surface of these novel BDD electrodes was significantly smoother than the commercially available, bulk grown BDD electrodes produced by Element Six, which exhibited ~9 μm surface roughness (R_a).

Table 1 also summarizes the electrical characterization of the sensing electrodes as well as their thickness and roughness values. As described above, the thickness of the BDD layer was optimized to yield sheet resistance values less than 25 Ω/sq., sufficiently low for negligible voltage drop across the electrode surface. The thickness of the insulating SiO₂ layer was decreased from 5 μm for *MA-1* to 1.5 μm for *MA-2* to avoid deeply recessed features which may interfere with the diffusion of analyte into the electrochemically active BDD areas.

In order to validate the performance gains provided by the UME arrays, a series of cyclic voltammetry experiments was conducted at a scan rate of 100 mV/s. The UME behavior can easily be confirmed by the sigmoidal shape of a CV curve performed with a well-defined

solution redox couple ferri/ferrocyanide [13, 26]. Both UME electrodes (*MA-1* and *MA-2*) yielded higher current density responses than *LO*, validating the use of UME arrays to improve electrode sensitivity. The CV plot of *MA-2* BDD array also yielded a sharp curve with sigmoidal shape indicative of ultramicroelectrode behavior, whereas the large-area BDD (*LO*) yielded a broader, diffusion-limited CV curve as shown in Figure 4. *MA-2* showed significantly higher current density than *MA-1*, further showing the signal magnitude benefit of larger UME separation. The current response of the *MA-1* electrode was also not entirely sigmoidal, indicating that even though those UMEs were showing non-diffusion limited behavior, they were also not separated far enough to enable their completely independent operation from each other. The deviation from sigmoidal behavior can also be partially attributed to the more recessed nature of the *MA-1* UMEs from the surface of the electrode (5 μm) as compared to that of *MA-2* UMEs (1.5 μm) [27].

3.3. BDD UME Arrays for Cadmium Detection

The electrochemical cell used in this work which consisted of a BDD UME array (working), a graphite rod (counter), and a reference electrode (Ag/AgCl). Electrochemical detection of cadmium at ppb levels requires extremely sensitive electrodes with good stability and reproducibility. Differential Pulse Stripping Voltammetry (DPSV) is a superior method for monitoring the concentration of cadmium down to low ppb levels as it eliminates background (non-Faradaic) currents. When the deposition potential (e.g. -1.5V) is applied to the sensing electrode, it concentrates the cadmium at the electrode surface from solution (reduction of Cd^{2+} to Cd^0), enhancing (lowering) the limit of detection. This is followed by an anodic stripping scan with differential pulses where the cadmium gives a signature current response at $\sim -0.8\text{V}$ that is proportional to the concentration of cadmium in the sample solution.

In order to demonstrate the use of DPSV and determine the electrochemical sensor performance of the fabricated BDD UME arrays, two UME arrays (*MA-1* and *MA-2*) as well as two unpatterned BDD macro electrodes were used to detect the cadmium content of a standard reference material (NIST 1640a natural water sample). Table 2 lists the electrode specifics of a bulk grown, commercially available BDD electrode (Bulk BDD, Element Six) as well as the unpatterned *LO* electrode and the BDD UME arrays *MA-1* and *MA-2*. A NIST sample with a certified cadmium content of 3.992 ± 0.074 ppb was tested with all four sensor electrodes as shown in Figure 5. The specific sensor response normalized to active area was the highest for the *MA-2* BDD with a peak height of 0.855 mA/cm^2 , over an order of magnitude higher than either the bulk grown BDD or the unpatterned *LO* electrode (Figure 5, inset). The background noise of the *MA-2* sensor was also the lowest at 3.12 nA , resulting in the best limit of detection value compared to the macroelectrode BDDs.

Figure 6 shows the differential pulse voltammogram obtained by depositing/stripping cadmium on an *MA-2* electrode followed by addition of cadmium standards to quantify the initial concentration. The cadmium stripping peaks occurred at approximately -0.75V for the NIST sample, and the peak height showed linear dose dependence upon addition of cadmium from a stock cadmium solution. The linear extrapolation using a 6-point calibration estimated the original cadmium content as being 4.16 ppb, which was accurate within 4.2% of the certified cadmium content of 3.992 ± 0.074 ppb. The sensitivity of the BDD sensor was determined to be $202.1 \mu\text{A/ppb/cm}^2$ from the slope of the linear regression curve, which was at least an order of magnitude higher than any other cadmium detecting sensors reported in literature [28–31]. It is also noteworthy that the algorithm yielded consistent, minor, and non-interfering lead and copper stripping peaks at -0.42V and -0.02V , respectively.

To further test the sensitivity of the *MA-2* BDD sensing electrode, a more complex urine medium (ProMedDx, LLC) was dosed with 0.25 ppb cadmium additions. Figure 7 shows a typical stripping portion of a differential pulse voltammogram obtained in urine by deposition and stripping of Cd along with the dependence of peak height and area with increased concentration. Prior to testing, the urine was treated with an electrochemical oxidation process. This was performed to degrade and mineralize organics that would otherwise chelate cadmium and render it inactive for electrochemical testing.[32, 33] The treated urine sample was also diluted two-fold with water and acetate buffer to maintain a controlled pH of 4.0. The urine sample yielded a slightly shifted cadmium peak at -0.9V along with minor peaks from zinc at -1.2V and copper at -0.06V (Figure 7). The current response indicated a very low (sub ppb) cadmium amount as expected from a healthy urine sample. The sensor effectively responded to a series of 0.25 ppb Cd additions showing a linear dose dependence as shown in Figure 7, inset. The *MA-2* sensing electrode yielded highly reproducible results for both peak height and peak area, and a sensitivity value of $284.5 \mu\text{A/ppb/cm}^2$ was obtained even in the presence of a complex matrix such as urine. Using the intercept of the post-calibration step, the initial concentration of cadmium was determined to be 0.08 ppb from peak area. Peak area was used instead of peak height due to the peak widening with increased cadmium concentration. This was in very good agreement with the cadmium result obtained from an ICP-MS analysis performed on the same urine sample (0.18 ppb). It is important to note that the amount of cadmium present in this healthy urine sample is very low (sub-ppb), nearing the LOD values for both methods. Owing to the ultramicroelectrode effect, the signal-to-noise ratio also improved compared to macroelectrode BDDs, allowing the detection of Cd at very low (<1 ppb) levels. The limit of detection in urine based on the signal-to-noise ratio ($S/N = 3$) was determined to be 0.0013 ppb.

4. Conclusions

In this work, we successfully demonstrated the fabrication of BDD arrays that showed a composite ultramicroelectrode behavior and yielded high, steady-state (non-diffusion limited) Faradaic currents. When used as a cadmium sensor, these electrodes showed increased sensitivity with enhanced LOD values for trace level detection in water and in urine. These microarray electrodes also showed long term stability without any significant sensitivity loss over 1000 scans with two year of usage. Both the BDD layer and the patterned SiO_2 layer remained intact without any mechanical defects (delamination or flaking), and they have endured repeated electrochemical scans as well as the chemical and electrochemical cleaning procedures applied in this work. The stability of the metal oxidation peaks as well as the reproducibility of the data suggests that these BDD UME arrays are excellent candidates for development of a rapid and reliable electrochemical sensor to detect trace levels of metals even in the presence of challenging matrices and interfering agents such as organic compounds and other metals. In addition to the presented work, these UME arrays are also being used in the detection of pesticides as well as other trace metals such as silver, zinc, lead, cobalt, and chromium.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

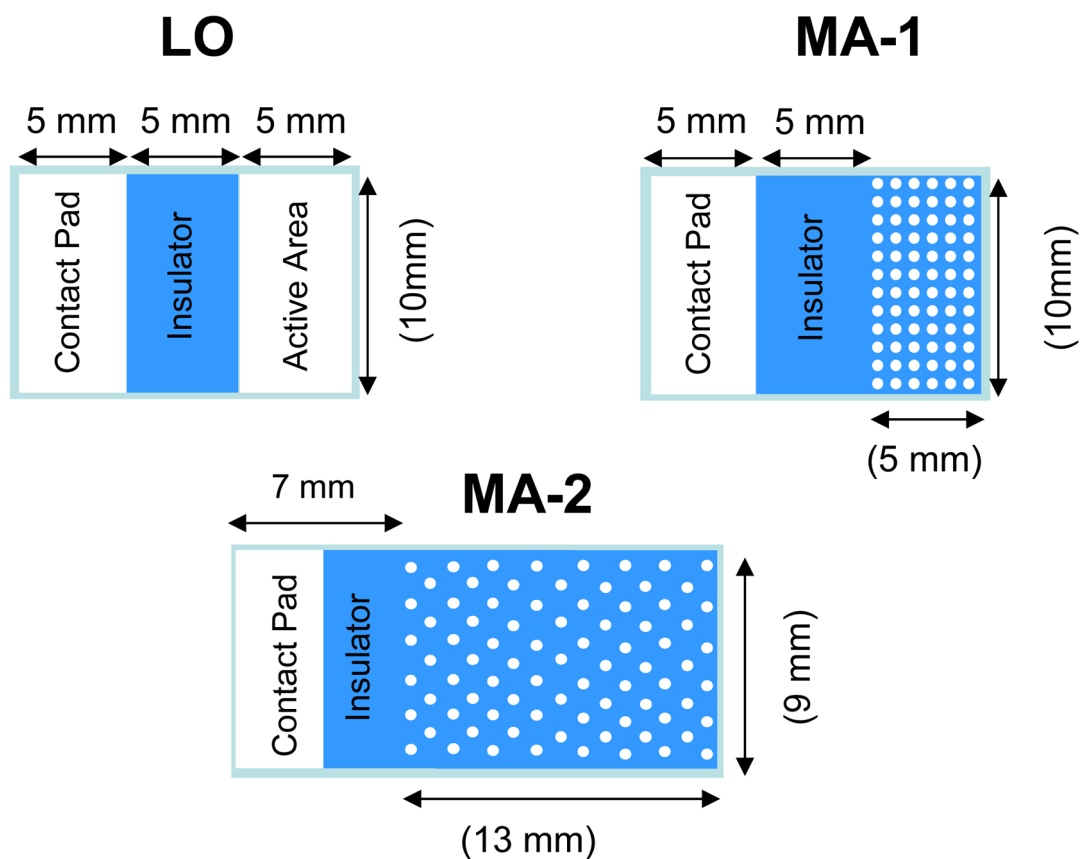
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Highlights

- An electrochemical sensor capable of detecting cadmium at parts-per-billion levels in urine.
- A novel fabrication method for Boron-Doped Diamond (BDD) ultramicroelectrode (UME) arrays.
- Unique combination of BDD arrays and a differential pulse voltammetry algorithm.
- High sensitivity, high reproducibility, and very low (nanoampere) noise levels.
- Opportunity for portable operation to assess on-site personal exposure.



Sensor Electrode	C ₂ C separation (μm)	UME Radius (μm)	# of UMEs	Sensor Area (cm ²)	Active Area (cm ²)	Area Coverage (%)
LO	N/A	N/A	N/A	0.5	0.5	100
MA-1	60	12.5	12,960	0.5	0.064	12.8
MA-2	120	10.5	8,662	1.17	0.030	2.56

Figure 1.

The schematic representation of two types of BDD ultramicroelectrode arrays (*MA-1* and *MA-2*) as well as an unpatterned BDD electrode (*LO*). Although the UME radii of both *MA-1* and *MA-2* were designed to yield 10 μm, the actual average UME radius for *MA-1* was ~12.5 μm due to overetching during processing.

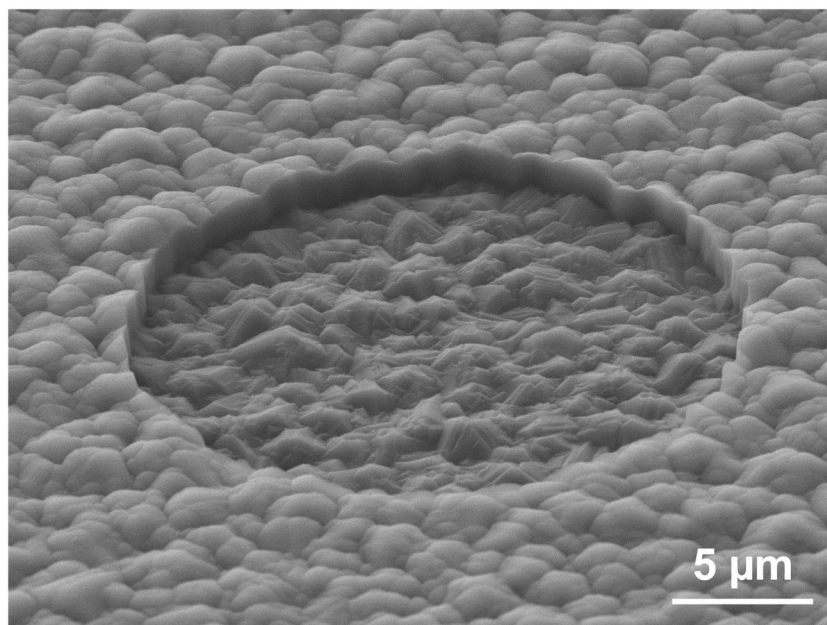


Figure 2.
A close-up SEM image of a fully processed BDD UME (*MA-2*) embedded within a SiO_2 insulating layer with 1.5 μm thickness.

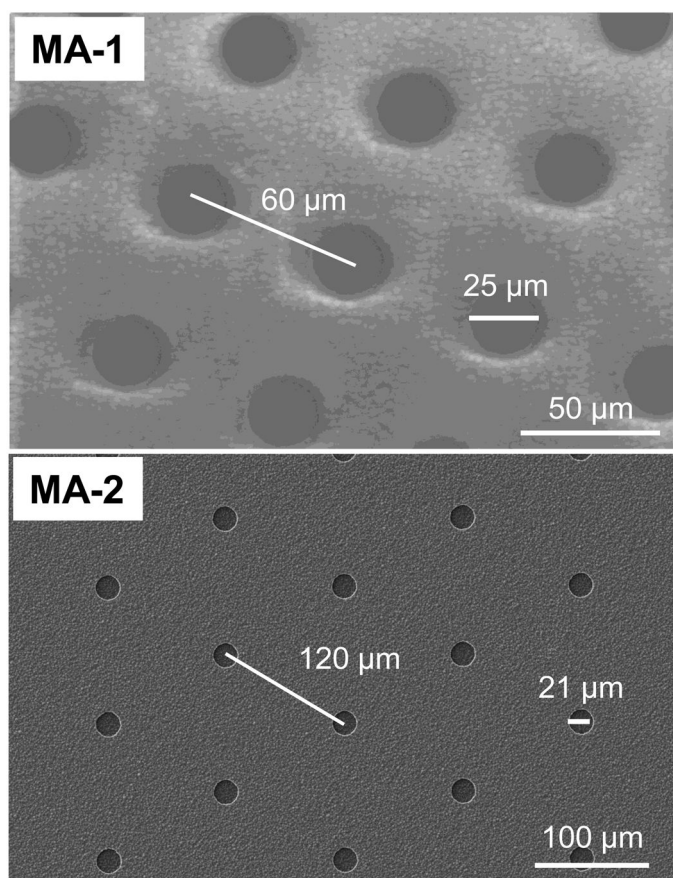


Figure 3. SEM Micrographs of *MA-1* and *MA-2* BDD UME arrays shown with their corresponding UME diameters and center-to-center distances.

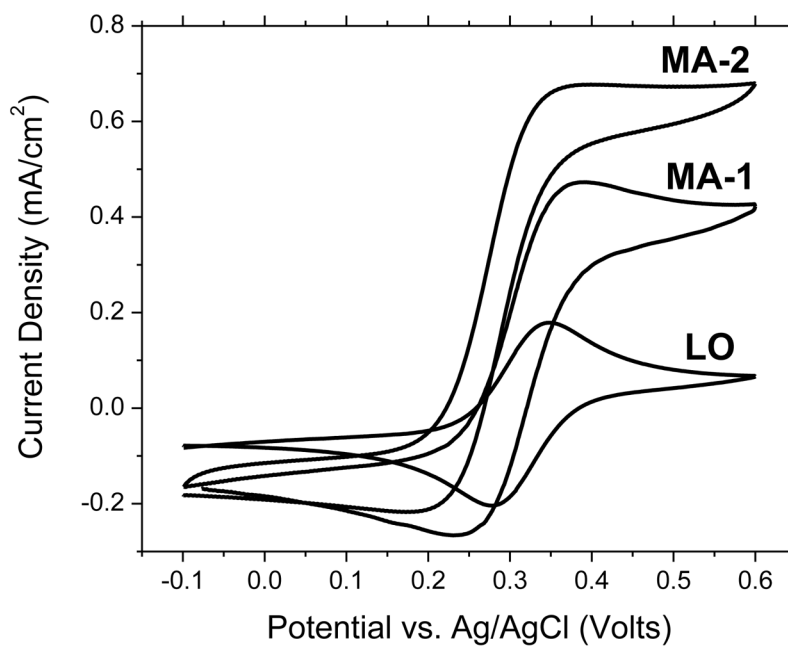


Figure 4. Sample CV plots of BDD sensor electrodes with ferri/ferrocyanide at a scan rate of 100 mV/s. Both *MA-1* and *MA-2* have sigmoidal behavior compared to the diffusion-limited behavior of the *LO* electrode.

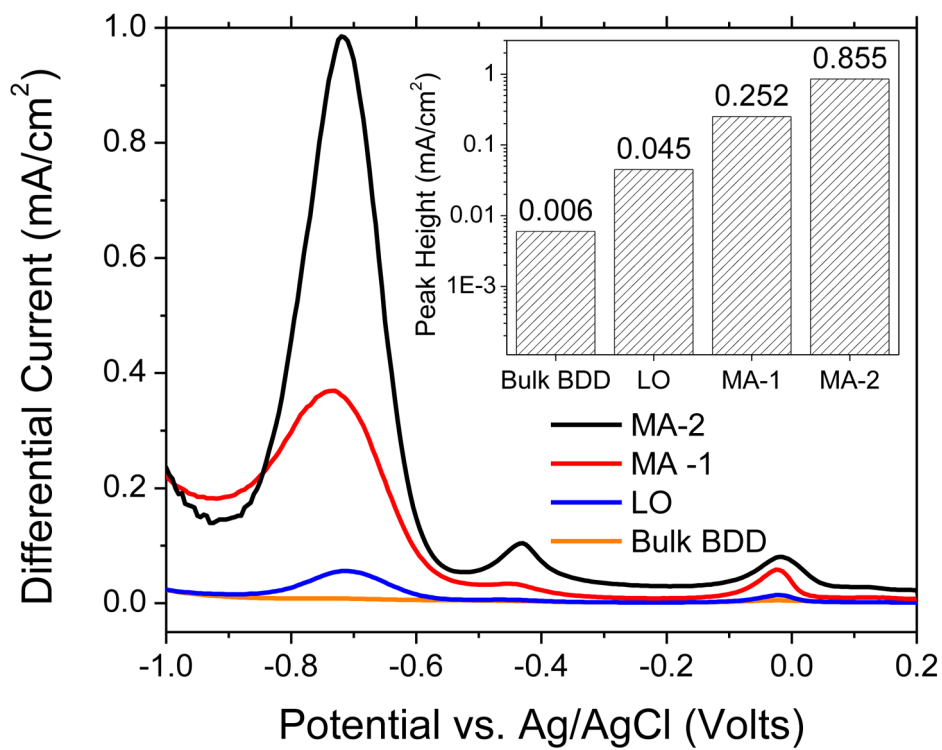


Figure 5. Signal comparison of various types of BDD sensing electrodes tested in a NIST natural water sample with 3.992 ppb innate cadmium.

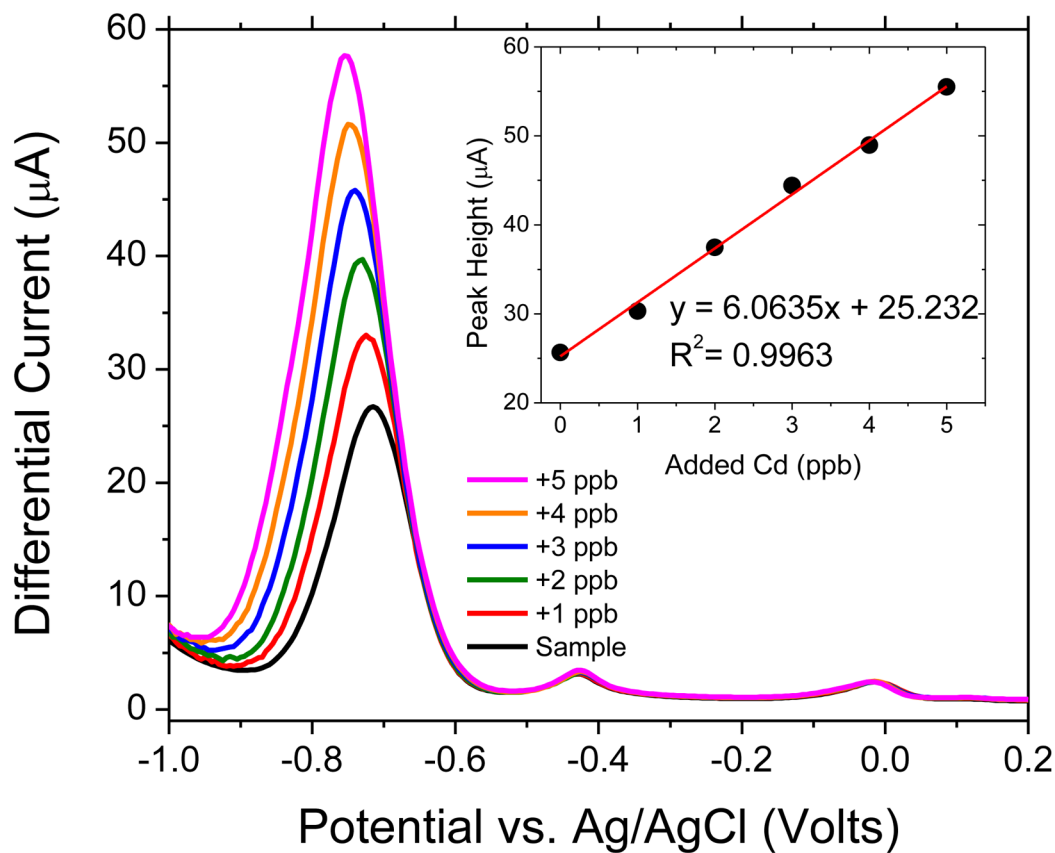


Figure 6. The detection and quantification of cadmium in a certified water sample (NIST 1640a). DPSV curves showed three peaks obtained from the stripping scan where the cadmium peak at -0.75V linearly increased upon addition of a stock cadmium solution (inset).

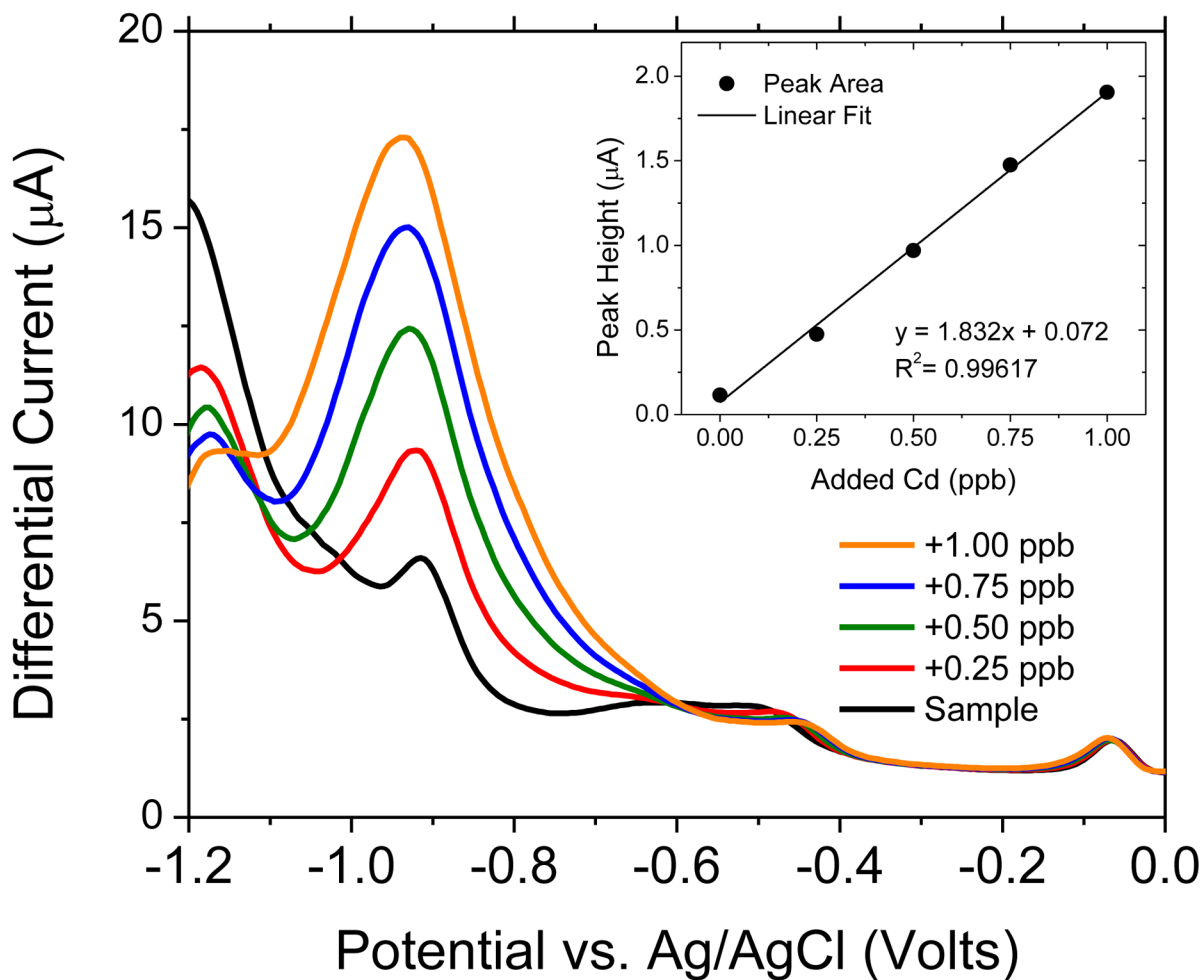


Figure 7. The detection of cadmium in a human urine sample (ProMedDx, LLC) at 0.25 ppb cadmium increments. Inset shows the linear concentration dependence of peak area as a function of added Cd amount.

Table 1

Thickness, electrical, and roughness data obtained from BDD sensors. Values are the average of 10–15 sensing electrodes obtained from a single 75 mm silicon wafer batch.

Sensor	Thickness (μm)			Resistance		Roughness (R_a , nm)
	PCD	BDD	SiO ₂	Sheet (Ω/sq)	Bulk ($\Omega\cdot\text{cm}$)	
LO	3.5	4.5	N/A	21.0	0.01	40.0
MA-1	8.8	4.0	5.0	24.8	0.01	44.2
MA-2	2.5	4.3	1.5	10.5	0.005	60.9

Table 2

Performance comparison of four BDD sensing electrodes tested in NIST water sample.

Sensor	Description	Total/Active Area (cm ²)	Cd Peak Height (mA/cm ²)	Noise Level (nA)	LOD (S/N&#e3) (ppb)
Bulk BDD	Macro: Bulk grown BDD	2 / 2	0.006	15.17	0.0151
LO	Macro: BDD on Si	0.5 / 0.5	0.045	7.49	0.0040
MA-1	UME: 12,960 microdots	0.5 / 0.064	0.252	6.67	0.0049
MA-2	UME: 8,662 microdots	1.17 / 0.03	0.855	3.12	0.0014