Fabrication of 2D-Material-Based Ionic Transistors

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***Primary CNF Tools Used: Heidelberg Mask Writer DWL-2000, ABM Contact Aligner,
Oxford 81 RIE, AJA Ion Mill, SC4500 Even-Hour Evaporator***

Abstract:

Traditional electronic field-effect transistors (FETs), which utilize electrons and holes as charge carriers, are indispensable in modern electronic devices such as integrated circuits and microprocessors. They form the backbone of today's digital technology by enabling efficient information processing, storage, and transmission. Despite ongoing challenges in the miniaturization of electronic transistors, ionic FETs offer distinct advantages, particularly biocompatibility and tunable conductance. Our project aims to fabricate ionic transistors using advanced 2D materials and address the limitation of low on-off current ratios in these devices.

Summary of Research:

The human brain, with its highly selective ionic transmission system, processes vast amounts of information and facilitates neural communication daily. To mimic the ultra-functional capabilities of the brain, nano-channeled ionic field-effect transistors that use ions like Na^+ and Ca^{2+} as carriers, similar to those in neural processes, show great potential for future applications. Such transistors are promising for artificial brain systems and memory devices like neuromorphic memristors due to their unique ability to maintain discrete conductivity states, which serve as memory storage units.

In order to replicate the ultra-selectivity of brain ionic channels and increase the on-off ratio, we focused on fabricating ionic transistors with nanochannels approaching the Debye length. Conventional microchannels, characterized by their short Debye lengths and discontinuous electric field effects, often result in the undesirable coexistence of both negative and positive ions. In contrast, the nanochannel design allows the electric field to penetrate the entire channel, predominantly permitting the passage of only a single ion type. This ensures a low energy consumption in the transistor, mirroring brain functions.

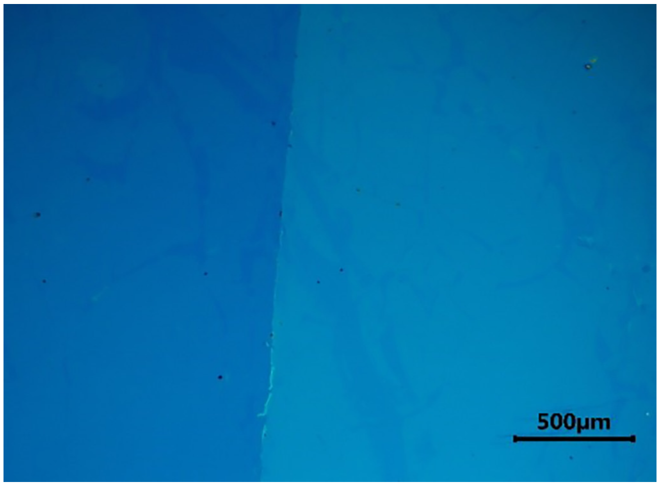
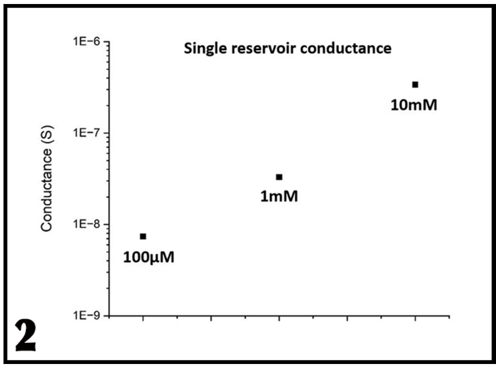


Figure 1: A stable 2D heterostructure is illustrated.

We began by preparing a silicon wafer with a 300 nm thermal oxide layer, cutting it into 1-inch by 1-inch pieces. To create the nanochannel ionic pathway, we deposited a monolayer of 2D Copper-Tetrakis (4-carboxyphenyl) porphyrin (CU-TCPP) by immersing the wafer pieces in a copper nitrate solution, capping them with hexane, and injecting TCPP solution using a syringe pump. After allowing the hexane to evaporate, the remaining solution was drained. Thereafter, a monolayer of molybdenum disulfide (MoS_2) was exfoliated and transferred onto the CU-TCPP-coated pieces, resulting in the formation of a stable 2D heterostructure, as illustrated in Figure 1.

To etch the MoS_2 monolayer into a 100 μm by 100 μm pattern, photolithography and the AJA ion mill at the Cornell NanoScale Facility were employed. Oxygen plasma then removed the photoresist cleanly. Next, we deposited 50 nm of silicon dioxide using the Oxford Atomic Layer Deposition



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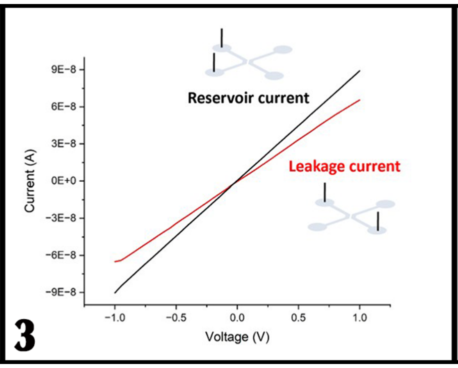

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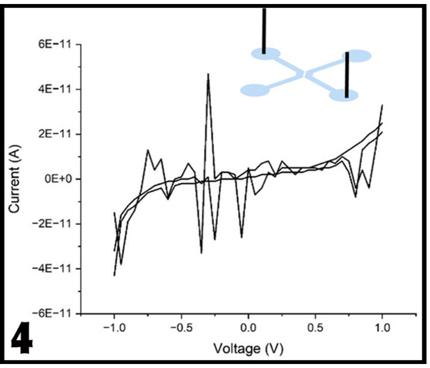

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FlexAL machine to serve as the insulating layer of the ionic field effect transistor. The gate electrode was fabricated by depositing 10 nm of titanium and 50 nm of gold with the Thermal/E-gun Evaporation System, followed by a lift-off process using hot N-Methylpyrrolidone (NMP) stripper. The source and drain channels were defined using SU-8 and photolithography, and subsequently etched with the Oxford reactive ion etching tool. Finally, capping the pieces with polydimethylsiloxane (PDMS) completed the fabrication process.

For the measurement of Single Reservoir Conductance, four holes were made in the PDMS, into which sodium chloride (NaCl) electrolyte was injected. Two silver electrodes were placed in the same reservoir. With ions flowing freely within the unobstructed single fluid channel, conductivity was observed, confirming the successful fabrication of the single reservoir. Figure 2 shows the relationship between the NaCl solution concentration and its conductance, indicating that as the concentration increases, the number of ions available for carrying electric current also increases, leading to higher conductance.

During the leakage test, electrodes were placed in two separate fluid channels rather than in the same one. Without a nanochannel allowing current to flow between the channels in this case, no current should have been detected when applying voltage if there was no leakage. However, as shown in Figure 3, when voltage ranging from -1V to 1V was applied, a leakage current of approximately 10^{-8} A was detected. This current is of the same order as that of a single connected reservoir, suggesting that some leakage was indeed occurring between the two fluid channels.

To address this issue, we applied Vapor Phase (3-Aminopropyl) triethoxysilane (APTES) treatment [1] to the PDMS to induce covalent bonding between SU-8 and PDMS, enhancing the sealing of the fluid channels.

After this optimization, we repeated the leakage test under identical conditions. This time, the current was around 10^{-11} A, which is three orders of magnitude lower than the previous leakage current, and no linear trend was observed in Figure 4. This minor current, likely due to the open holes, was close enough to zero to indicate that there was no leakage, confirming the successful fabrication of a leakage-free device, ready for future experiments and innovations.

Conclusions and Future Steps:

In conclusion, our 2D material-based ionic field effect transistors demonstrate potential for applications in future Neuromorphic Computing systems by simulating brain functions. The use of Oxygen Plasma effectively removed the photoresist, while Hot NMP facilitated the lift-off process. The leakage between source and drain channels was minimized through APTES treatment of PDMS, resulting in a non-leakage current of approximately 10^{-11} A under a voltage range of -1V to 1V. Future work should focus on testing and measuring the conductance of different organic molecule cages, which could lead to the selective manipulation of ion types passing through the transistors.

Acknowledgements:

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References:

[1] Micromachines 2015, 6(12), 1923-1934.