NANOFLUIDICS

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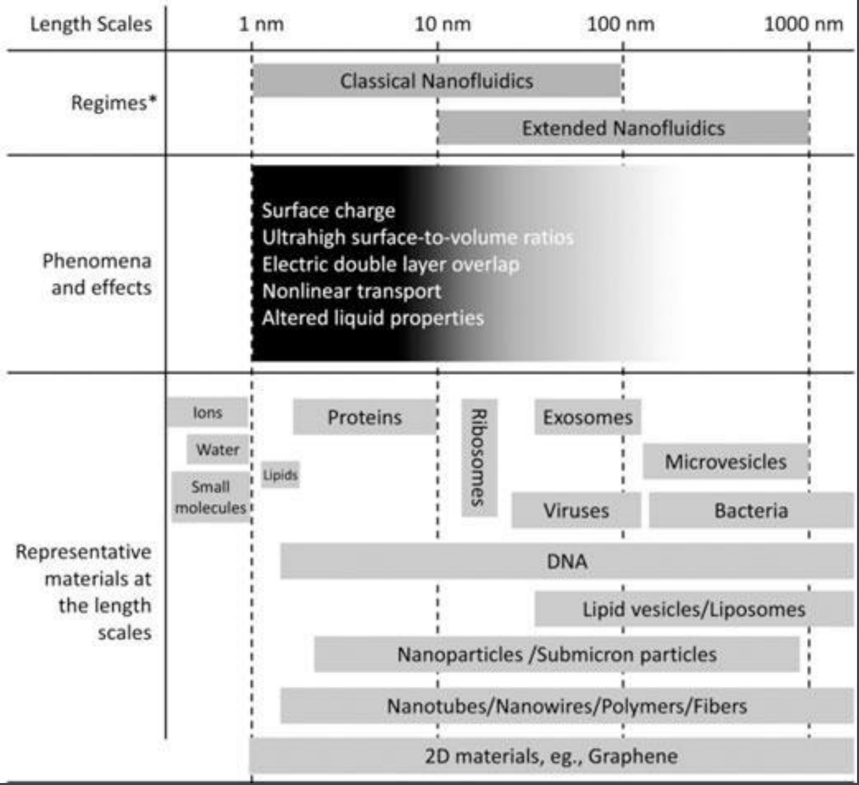
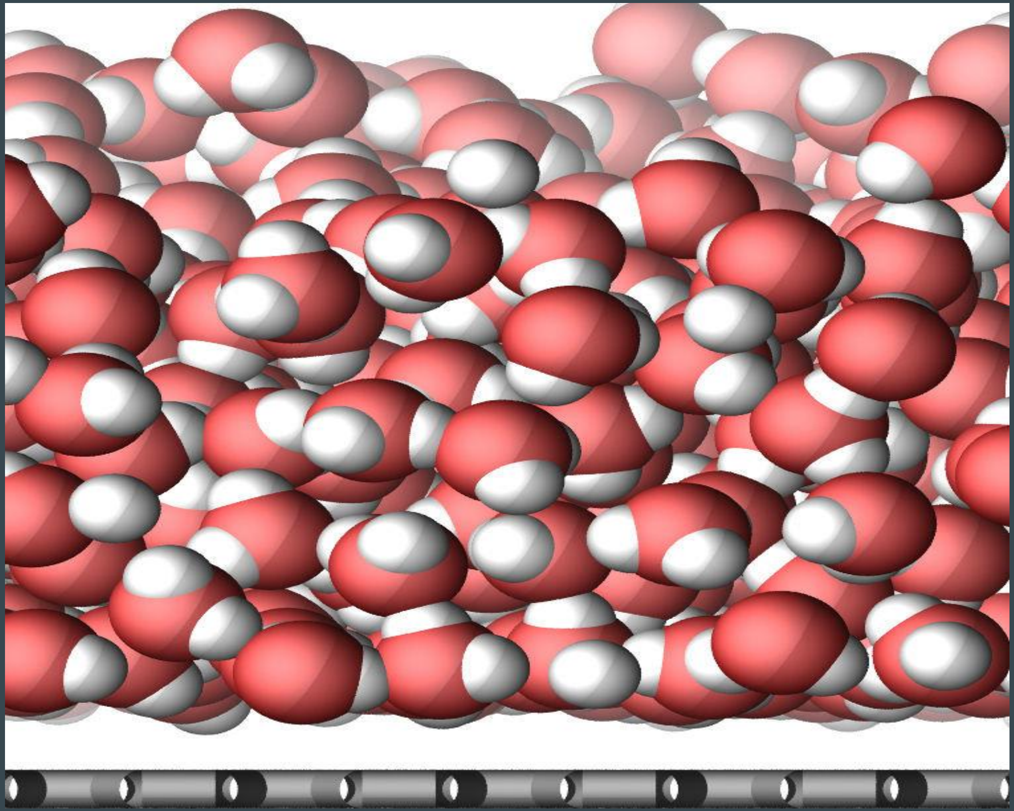
Basics

- Fluid is a substance that continually flows under an applied shear stress. Fluids are a phase of matter and include liquids, gases and plasmas. They are substances with zero shear modulus, or, in simpler terms, substances which cannot resist any shear force applied to them.
- Fluidics is the study and technique of using small interacting flows and fluid jets for functions usually performed by electronic devices. The physical basis of fluidics is pneumatics and hydraulics, based on the theoretical foundation of fluid dynamics. The term *fluidics* is normally used when devices have no moving parts, so ordinary hydraulic components such as hydraulic cylinders and spool valves are not considered or referred to as fluidic devices.
- A jet of fluid can be deflected by a weaker jet striking it at the side. This provides nonlinear amplification, similar to the transistor used in electronic digital logic. It is used mostly in environments where electronic digital logic would be unreliable, as in systems exposed to high levels of electromagnetic interference or ionizing radiation.
- Nanotechnology considers fluidics as one of its instruments. In this domain, effects such as fluid-solid and fluid-fluid interface forces are often highly significant.

Relative Scale





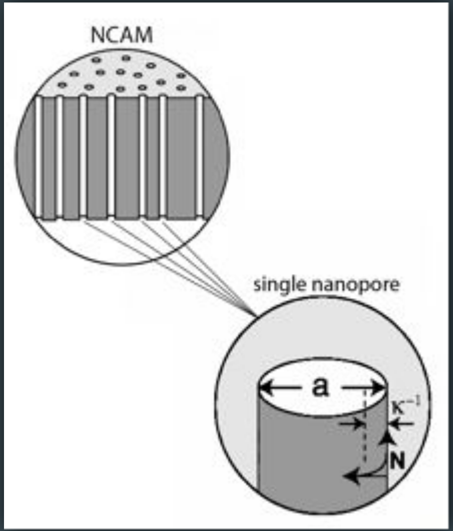
Water molecules (oxygen in red, hydrogen in white), next to a graphene sheet (in grey)

Central Idea

Nanofluidics is the study of the behavior, manipulation, and control of fluids that are confined to structures of nanometer (typically 1–100 nm) characteristic dimensions (1 nm = 10^{-9} m). Fluids confined in these structures exhibit physical behaviors not observed in larger structures, such as those of micrometer dimensions and above, because the characteristic physical scaling lengths of the fluid, (*e.g.* Debye length) very closely coincide with the dimensions of the nanostructure itself.

When structures approach the size regime corresponding to molecular scaling lengths, new physical constraints are placed on the behavior of the fluid. For example, these physical constraints induce regions of the fluid to exhibit new properties not observed in bulk, *e.g.* vastly increased viscosity near the pore wall; they may affect changes in thermodynamic properties and may also alter the chemical reactivity of species at the fluid-solid interface.

A particularly relevant and useful example is displayed by electrolyte solutions confined in nanopores that contain surface charges, *i.e.* at electrified interfaces, as shown in the nanocapillary array membrane (NCAM) in the accompanying figure.

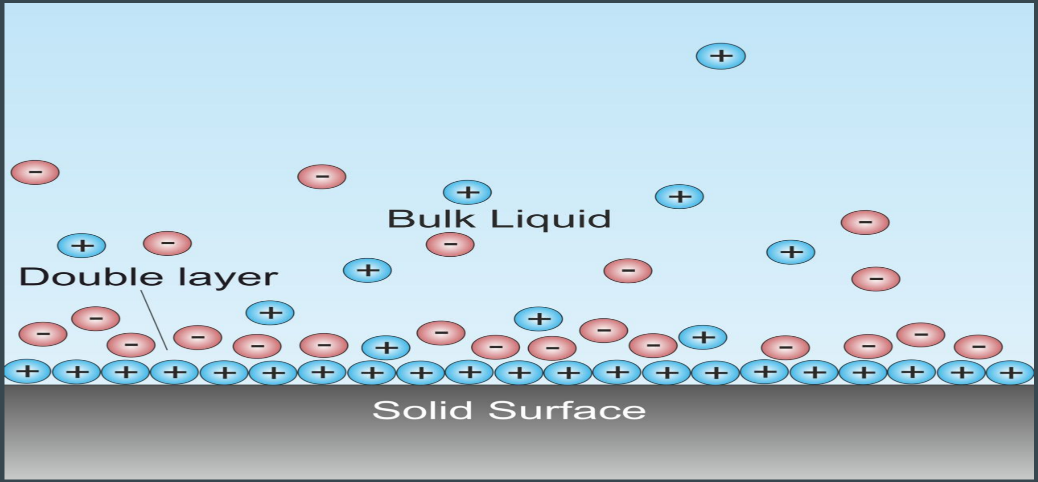


Schematic diagram of one particular realization of nanofluidics in a nanocapillary array membrane, or NCAM. The NCAM is composed of a large number of parallel nanocapillaries, each of which have a pore radius, *a/2*, which is approximately the same size as the Debye length, κ^{-1}. The electrical double layer is characterized by a counter-ion distribution, *N*, which is largest at the pore wall and decays toward the center of the pore.

Theory

All electrified interfaces induce an organized charge distribution near the surface known as the electrical double layer. In pores of nanometer dimensions the electrical double layer may completely span the width of the nanopore, resulting in dramatic changes in the composition of the fluid and the related properties of fluid motion in the structure.

The drastically enhanced surface-to-volume ratio of the pore results in a preponderance of counter-ions (*i.e.* ions charged oppositely to the static wall charges) over co-ions (possessing the same sign as the wall charges), in many cases to the near-complete exclusion of co-ions, such that only one ionic species exists in the pore. This can be used for manipulation of species with selective polarity along the pore length to achieve unusual fluidic manipulation schemes not possible in micrometer and larger structures.



Electronic properties

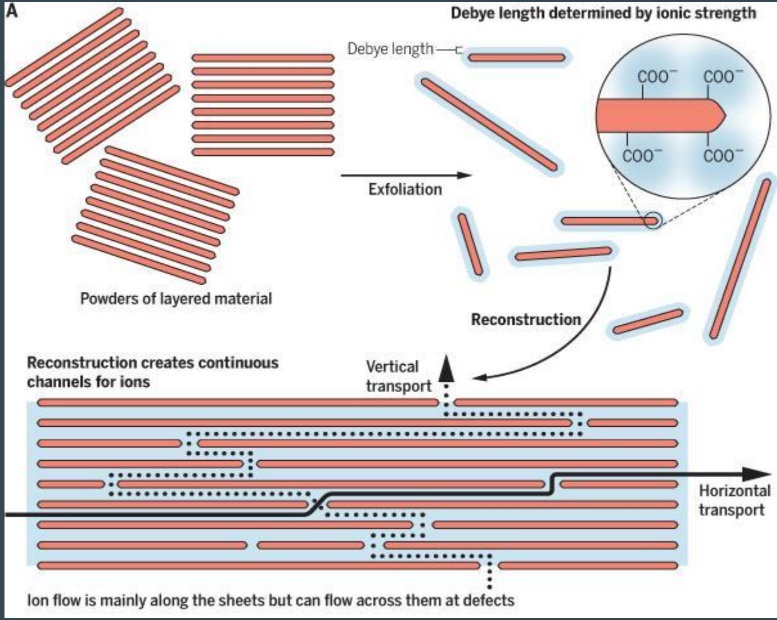
The remarkable electronic properties of graphene and related two-dimensional (2D) materials result from the confinement of electrons within the material. Similarly, the interstitial space between 2D materials can enable the 2D confinement of ions and electrolytes and alter their transport. Many different 2D sheets can be obtained by exfoliation of natural layered materials, and an exfoliation-reconstruction strategy can convert powders of layered materials into continuous, robust bulk forms in which lamellar nanochannels occupy a substantial volume fraction.

The surface properties and the spacing of the 2D nanochannels can be conveniently controlled by modifying the starting sheets. No matter how electrolytes pass through the film, horizontally or vertically, they flow through the same set of 2D channels, with the only difference being flux.

Enhanced ionic conductivity through 2D nanofluidic membranes can be used to create electrochemical devices, especially for those with in-plane geometry . It is also very attractive for designing new ion-selective membranes, potentially allowing new applications under unprecedentedly extreme conditions.

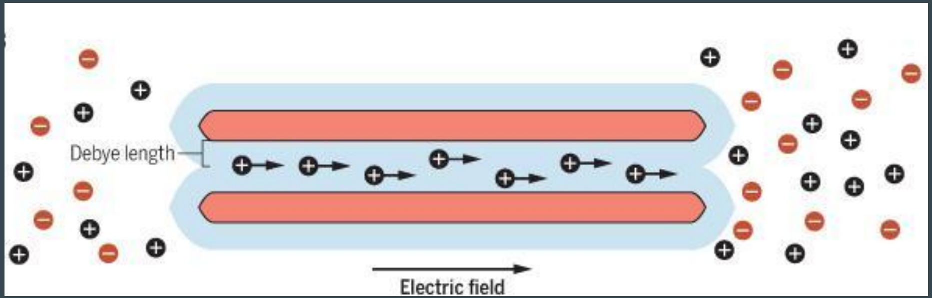
Confining Ion Flow

Lamellar film with massive arrays of 2D nanofluidic channels can be made by the exfoliation-reconstruction approach, as illustrated with models of graphene oxide (GO) sheets that are terminated with negatively charged carboxyl groups.



Flow Direction

Debye layers of neighboring sheets overlap to create unipolar 2D ion channels with greatly enhanced cation conductivity. The electrolytes follow a path determined by their ionic interaction with the carboxyl ions present at all the terminals of the graphene layers.



Fabrication

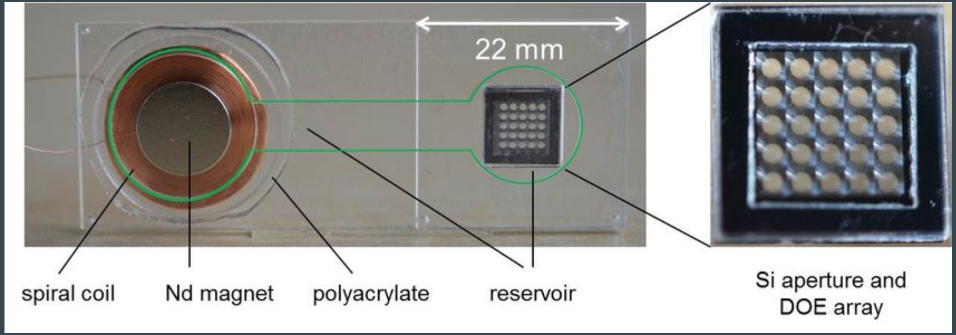
Nanostructures can be fabricated as single cylindrical channels, nanoslits, or nanochannel arrays from materials such as silicon, glass, polymers and synthetic vesicles. Standard photolithography, bulk or surface micromachining, replication techniques (embossing, printing, casting and injection molding), and nuclear track or chemical etching, are commonly used to fabricate structures which exhibit characteristic nanofluidic behavior.

The different fabrication techniques are listed below:

- Electron beam lithography
- Focussed ion beam technique
- Spacer technique
- Ion selective polymer
- Nanoporous material
- Etching and bonding

Applications

- Owing to the small size of the fluidic conduits, nanofluidic structures are naturally applied in situations demanding that samples be handled in exceedingly small quantities, including analytical separations and determinations of biomolecules, such as proteins and DNA, and facile handling of mass-limited samples.
- One of the more promising areas of nanofluidics is its potential for integration into microfluidic systems, i.e. lab-on-a-chip structures. When incorporated into microfluidic devices, can reproducibly perform digital switching, allowing transfer of fluid from one microfluidic channel to another, selectivity separate and transfer analytes by size and mass, mix reactants efficiently, and separate fluids with disparate characteristics.
- In addition, there is a natural analogy between the fluid handling capabilities of nanofluidic structures and the ability of electronic components to control the flow of electrons and holes. This analogy has been used to realize active electronic functions such as rectification and field-effect and bipolar transistor action with ionic currents.
- Application of nanofluidics is also to nano-optics for producing tunable microlens array.

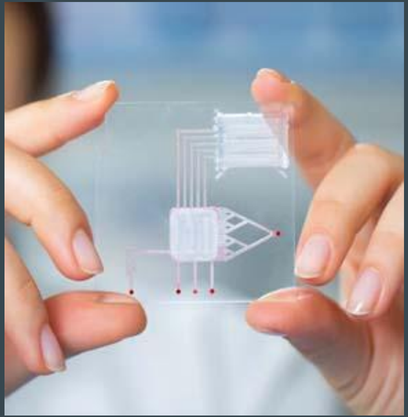


Impact

- Nanofluidics have had a significant impact in biotechnology, medicine and clinical diagnostics with the development of lab-on-a-chip devices for PCR (Polymerase Chain Reaction) and related techniques.
- Attempts have been made to understand the behaviour of flowfields around nanoparticles in terms of fluid forces as a function of Reynolds and Knudsen number using computational fluid dynamics .
- The relationship between lift, drag and the Reynolds number has been shown to differ dramatically at the nanoscale compared with macroscale fluid dynamics.

Advantages

- Significant reduction in sample volumes required for analysis.
- Enables experiments to be carried out to take advantage of laminar flow conditions.
- High surface to volume alters the bulk properties to a great extent.



Lab-on-a-chip

Challenges

There are a variety of challenges associated with the flow of liquids through carbon nanotubes and nanopipes.

A common occurrence is channel blocking due to large macromolecules in the liquid. Also, any insoluble debris in the liquid can easily clog the tube. A solution for this researchers are hoping to find is a low friction coating or channel materials that help reduce the blocking of the tubes. Also, large polymers, including biologically relevant molecules such as DNA, often fold, causing blockages.

Typical DNA molecules from a virus have lengths of approx. 100–200 kilobases and will form a random coil of the radius some 700 nm in aqueous solution at 20%. This is also several times greater than the pore diameter of even large carbon pipes and two orders of magnitude the diameter of a single walled carbon nanotube.

That’s all Folks!