Progress through Mechanics: Small-scale Gaps

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In his 1959 talk titled, "There's plenty of room at the bottom," Nobel Laureate, Professor Richard Feynman predicted that innovations that allow for "manipulating and controlling things on a small-scale" should be possible [1]. Advances in manufacturing have triggered many instances of such innovations, and promise to provide more opportunities for exploring length scales from a micrometer (μm) down to a nanometer (nm). Miniaturization of originally large-scale technologies to the size of a credit card, or even a single chip, has made mass-production at low costs feasible [2, 3]. While efforts are being channelled in this direction, there remains a critical need for precision tools that can advance an understanding of the fundamental science at small-scales, and, in turn, can accelerate the progress towards mass-production.

Small-scale gaps with sizes in the nm-μm range are leading examples of such precision tools. This range corresponds to the length scales of common particles such as biological macromolecules, cells, and metallic nanoparticles. For instance, our red blood cells are about $10\,\mu$m in size. Gold and silver nanoparticles causing exquisite colors in stained glass windows, such as the rose window of the Notre Dame Cathedral in Paris, have sizes on the order of 10-100 nm [4]. Gaps with sizes comparable to such common particles are ideal for manipulating and controlling them, and also for characterizing fields, forces and flows at small-scales.

Small-scale gaps have been fabricated using either bottom-up or top-down approaches for numerous applications [5]-[11]. Bottom-up approaches build devices molecule by molecule to generate the desired structure. A protein containing a nanometer-scale gap, and self-assembled into a lipid bilayer membrane, was used for detecting DNA by monitoring the ionic conductance of the gap in [7]. Top-down approaches are based on reducing dimensions from large to small, and typically involve advanced fabrication techniques. A 91 nm gap formed between metal electrodes was used for measuring the dielectric properties of single molecules as a function of frequency in [9]. A 35 nm gap formed between polysilicon electrodes was used as part of a fluidic transistor that controls the flow of ions in [11].

Programmability is a key feature absent in the gaps mentioned above. A gap that can be programmed to a desired size can be useful for a wider range of applications. A promising method to achieve such programmable gaps involves a precision variation of the separation between two optically flat surfaces held parallel to each other [12]. Existing designs [13]-[16] provide many choices, including atomically smooth mica films and fused silica plates, for forming such gaps. However, these designs do not address the critical features of (i) maintaining precise parallelism between the flat surfaces to ensure gap uniformity and (ii) robust gap control in the presence of uncertainties [17, 18] at small-scales. The following applications are uniquely enabled by a uniform and robustly programmable small-scale gap:

1. Rapid DNA Pattern Replication: A novel stamping technique proposed in [19] allows for duplicating a DNA pattern from a master to a secondary substrate. This technique can be applied to DNA microarrays, potentially reducing their unit cost from the current value of $500 to $50. The low cost can make DNA analysis a routine procedure for early diagnosis of diseases such as Alzheimer's, AIDS, and liver cancer [20]. However, the promise of this technique cannot be realized until the stamping step

is optimized. This step involves maintaining a uniform gap on the order of 10 nm between the substrates to enable pattern transfer. A robust parallel-plate construct maintaining a nanometer-scale gap is directly applicable to this problem. Further, dynamic characterization of DNA binding events can enable understanding the replication kinetics.

2. Size-based Filtrations: Porous membranes are used in biotechnology and pharmaceutical industries to sieve biological macromolecules such as proteins and nucleic acids [21]. However, size-selectivity of such membranes is limited by the distribution of pore sizes about a nominal value [22]. A robust small-scale gap can mimic a pore having a controlled size. An atomic-scale resolution for the variation of the gap can ensure high size-selectivity for the sieving of nanoparticles [23]. A parallel combination of many gaps can enable faster separations, and can be part of high-throughput automated systems used for diagnostics, drug discovery, and genomic and proteomic analyses [24, 25].

3. Characterization of Near-field Physics: A robust small-scale gap formed between parallel plates can be used to experimentally characterize near-field physical phenomena at various gap sizes in the nm-μm range. Example phenomena include radiative heat transfer and quantum-dynamic forces, such as Casimir forces [26]. Near-field radiative heat transfer has applications in thermophotovoltaics [27], an area that focuses on generating electricity from infrared radiation [28]. Understanding Casimir forces is essential from the standpoint of a related phenomenon called stiction, which adversely affects the fabrication of most MEMS devices [29].

4. Non-conventional Lithography: Feature resolutions possible with industrial lithography based on optical projection are diffraction-limited. Non-conventional techniques such as (i) contact, (ii) plasmon, and (iii) nano-imprint lithographies can generate much smaller features. In such techniques, a robust and uniform nanometer-scale gap, or contact (zero gap), needs to be maintained between the mask and the wafer.

In summary, programmable small-scale gaps formed between optically flat surfaces are an enabling technology for many promising applications, some of which are envisioned above. To form such gaps, an integrated approach based on mechanics is necessary. Such an approach should take into account not only the design, but also modeling and control [30]. Any effort involving the design, fabrication, and practical use of small-scale gaps should be initiated by inter-disciplinary teams composed of personnel with diverse skill sets. The inter-disciplinary work can bring fresh perspectives, and catalyze novel approaches to challenging problems. Such meaningful work can potentially groom into long-term collaborations that make impactful contributions to diverse fields, such as genomic and proteomic analyses, medical diagnostics, lithography, energy, and micro/nano systems. The extent of possibilities can only be left to one's imagination, because there surely seems to be, as Professor Feynman [1] believed, "plenty of room at the bottom."

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