Nanoscale Science and Technology Plenary Session
Room On Demand - Session NP-Invited On Demand

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NP-Invited On Demand-1 Atom-Defined Silicon Circuit Elements For Fast, Low Power Computing*, Robert Wolkow,* University of Alberta and The National Institute for Nanotechnology, Canada **INVITED**

CMOS based computers cannot be made substantially more energy efficient or faster. Fast, low power field controlled computing schemes believed capable of reviving Moore's law have not been physically realizable, until now. In such an approach binary information is encoded in spatial charge arrangements among quantum dots. Available quantum dots had been too large, too irregular, and too prone to debilitating charge trap effects. By reducing the quantum dot to a single silicon atom we have made the single electron charging energy very large resulting in dramatically improved noise immunity while also gaining near perfect homogeneity of components and eliminating charge traps. These structures are absolutely stable to over 200 C. And crucially, the silicon atom printing process has been automated and rendered virtually error free.

We will discuss how the atom-scale circuitry works and why it consumes little power ("Binary Atomic Silicon Logic", Nature Electronics, 1, 636-643). Atom defined binary wires will be shown. These transmit information extremely rapidly and without the use of conventional current and as a result experience virtually no I^2R heating. We will also show a working binary logic gate.

The A.I. automated fabrication process and atomic editing will be explained. Also the merging of regular CMOS with atom scale circuitry will be shown. This hybrid CMOS/Atom approach minimizes time to deployment. We can use CMOS circuitry where it is adequate and deploy the atom circuitry as embedded enhancements to reduce power, increase speed, or achieve all-new functions. Three applications will exemplify the advantages of this approach.

1. A neural network simulator will be described that has the potential to deliver Gibbs samples, obviating MCMC sampling when performing unsupervised training on unlabeled data (Phys. Rev. Lett., 121, 166801).
2. The low power prospects of our circuitry are shown by simulating the Google TPU with an atom-defined MXU. Clocking power is reduced 10,000x at 1 GHz. Alternatively, by allowing today's power consumption (limited to 100 W/cm2 dissipation) clocking of 1 THz becomes achievable.
3. The MXU is for now out of reach because it requires millions of atom printing steps. A practical, ~thousand atom goal is an extremely low power and fast analog to digital converter.

NP-Invited On Demand-7 Seeing the Hidden Interface: Revealing Nanoscale Mechanisms of Contact, Adhesion, and Friction by *in situ* Experiments*, Robert Carpick,* University of Pennsylvania **INVITED**

Richard Feynman, in his famous and visionary 1959 lecture "There's Plenty of Room at the Bottom", included discussion of the ways in which friction, wear, and lubrication would be different at small scales. It is now well understood that, as technology scales shrink, tribological interactions – friction, adhesion, and wear – play increasingly dominant roles. This can be problematic (e.g., extremely high friction that prevents motion), or can offer solutions (e.g., using adhesion to drive the formation and stability of nanostructures). The biggest challenge in exploring and exploiting these scientific and technological issues is that the interface between two materials is hidden from view. Recently, advances in *in situ* methods have enabled tribological mechanisms at previously inaccessible interfaces to be studied with unprecedented resolution and insight. We will discuss the application of two *in situ* experimental methods to develop new, physically-based insights into tribological processes.

I will first discuss using a novel method based on atomic force microscopy (AFM) to study the formation of anti-wear tribofilms derived from additives present in lubricating liquids. These films are crucial for protecting contacting, sliding parts in machinery from damage by forming during use. AFM is conducted in additive-containing oils to monitor the growth, morphology, and physical properties of tribofilms *in situ* during sliding of a well-defined single asperity contact geometry. We show that the famous molecule zinc dialkyldithiophosphate (ZDDP) functions via surface-based nucleation, growth, and saturation of ZDDP antiwear tribofilms as a function of sliding time. Based on these results, a mechanism for explaining the mysterious self-limiting growth of these films is proposed. We also show that 5 nm diameter zirconia nanoparticles dispersed in a lubricant can also form protective films on surfaces, opening a pathway for more environmentally-friendly additives that can enable energy-saving low viscosity lubricants.

We will then discuss new insights into nanoscale adhesion and wear[1] achieved using *in situ* transmission electron microscopy (TEM) wear tests. For silicon, diamond, and diamondlike carbon, we observe different modes of wear, all distinct from classic wear models. We also see a strong, reversible, sliding-history dependence of adhesion between silicon nanoasperities, attributed to shear-induced removal of adsorbates. Finally, I will preview new results applying the technique to the study of contact between two-dimensional materials including MoS_2.

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