DHIRANI GROUP

Quantum Nanoengineered Materials/Devices: Designer Quantum Systems from the Bottom-Up

When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. … We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc….
R. Feynman, APS 1959, "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics."

A theme of the Dhirani group's research is to use nanostructures as building blocks to fabricate quantum systems. Nanostructures exhibit a strong link between their structure and behaviour. Further, there have been significant advances in the discovery and synthesis of a wide variety of nanostructures with controlled structure. A well-known example is "quantum dots" which exhibit strongly size-dependent optical properties; their discovery and development garnered a 2023 Nobel prize. As a result, nanostructured materials have a "designer" nature that can be controlled from the bottom-up through choice of nano-building block and material architecture. A theme of the Dhirani group is exploit this control to shed light on previously observed but not well understood quantum phenomena, e.g., strongly correlated electrons, which are at the heart of exotic quantum phenomena such as high Tc superconductivity and heavy Fermions. In addition, new combinations of nanobuilding blocks can lead to observation of new phenomena and devices.

Fig 1 shows an example of a quantum nanostructured material developed by the Dhirani group following this bottom-up approach. These materials are a new class of nanosheets comprising gold metal particles electrically connected or "linked" via insulating or semiconducting "molecular wires" (quantum particle-in-a-box-type energy levels). While classical wires exhibit *__linearly increasing__* resistance with increasing wire length (longer wires have more scattering and higher resistance), these materials exhibit *__exponentially__* changing resistance with linker length. For insulating linkers, resistance *__increases exponentially__* due to quantum tunneling; for particle-in-a-box linkers, resistance *__decreases exponentially__* with increasing linker length due to quantum charge transport through the material's energy levels (longer molecule wires have more closely spaced energy levels and lower transport barriers: see Fig. 2). Studies of these and other new materials and devices are ongoing.

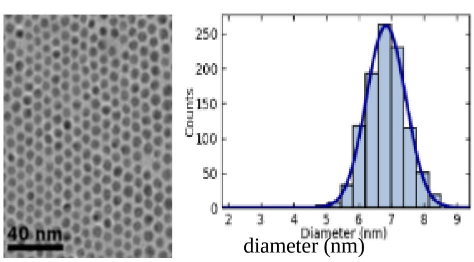

Fig. 1 Metal-linker Nanosheets fabricated by the Dhirani group Ref [3]

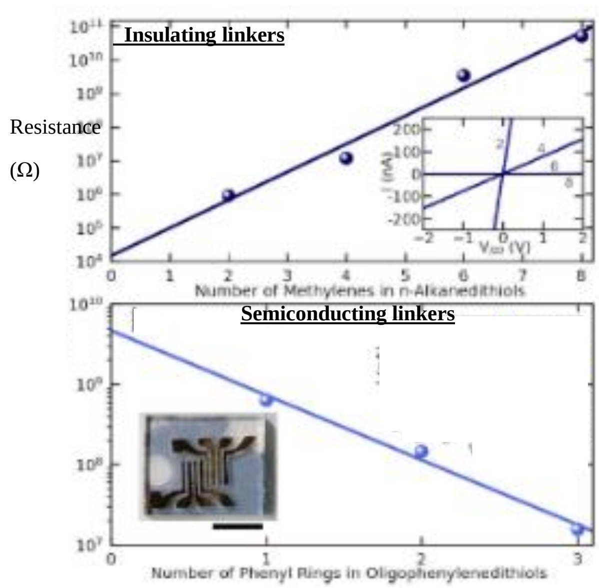

Fig. 2 Quantum Resistance exhibited by nanosheets: tunneling vs particle-in-a-box type barriers Ref [3].

Building on these results and depending on student interest, students have an opportunity to:

- Combine metal nanostructures and atoms or molecules and study the range of resulting quantum behaviours exhibited by such materials; e.g. strongly correlated electrons; or
- develop their potential device applications such as quantum electrochemistry, a field the Dhirani group is pioneering, and nanostructured direct solar-to-hydrogen energy conversion devices.

DESCRIPTION OF STUDENT PARTICIPATION:

Students will begin by performing a literature review. In the first phase of an experiment, they will fabricate and characterize nanostructured materials/devices. In the second phase of the experiment, students will help take measurements of and/or apply material properties (electrical, magnetic, optical).

[1] Zabet-Khosousi, A. and **Dhirani, A.A.**, 2008. Charge transport in nanoparticle assemblies. *Chemical reviews*, *108*(10), pp.4072-4124.
[2] M. Tie and **A.-A. Dhirani.** "Coulomb effects and exotic charge transport in nanostructured materials." *21st Century Nanoscience – A Handbook.* Ed. K. Sattler. Milton Park: Taylor and Francis (CRC Press), 2018.
[3] Gravelsins, S., Park, M.J., Niewczas, M., Hyeong, S.K., Lee, S.K., Ahmed, A. and **Dhirani, A.A.**, 2022. Large emergent optoelectronic enhancement in molecularly cross-linked gold nanoparticle nanosheets. *Communications Chemistry*, *5*(1), p.103.