Enhancing Radiative Heat Transfer With Silicon Metasurfaces

Thermal radiation is a universal physical phenomenon of great importance for different disciplines of science and engineering. In recent years, there has been a renewed interest in this topic due to the discovery that radiative heat transfer between two bodies can be drastically enhanced if they are brought sufficiently close to each other. This enhancement, which occurs when the separation is smaller than the thermal wavelength (10 microns at room temperature), is due to the contribution of evanescent waves that dominate the near-field regime. The fact that this near-field radiative heat transfer (NFRHT) between closely spaced bodies can overcome the far-field limit set by the Stefan-Boltzmann law for black bodies has now been verified in a variety of experiments exploring different materials, geometrical shapes, and gaps ranging from micrometers to a few nanometers.

In this context, the question on the fundamental limits of thermal emission is attracting a lot of attention. So far, the largest NFRHT enhancements have been reported for polar dielectrics (SiC, SiO2, SiN, etc), in which thermal radiation is dominated by surface phonon polaritons. Now, in a work published in Physical Review Letters, the IFIMAC researchers Víctor Fernández Hurtado, Francisco J. García Vidal and Juan Carlos Cuevas, IFIMAC researchers and members of the Department of Theoretical Condensed Matter Physics, together with Professor Shanhui Fan (Stanford University), have shown that metasurfaces of doped silicon can be used to boost NFRHT. In particular, they demonstrate that one can design silicon metasurfaces that not only exhibit a room-temperature NFRHT much larger than that of bulk Si or other proposed periodic structures, but they also outperform the best unstructured polar dielectric. The underlying physical mechanisms responsible for this striking behavior are the existence of broadband spoof surface-plasmon polaritons (SPPs) in doped silicon and the ability to...
tune via nanostructuration the dispersion relation of these SPPs that dominate NFRHT in this structure. This work illustrates the great potential of metasurfaces for the field of radiative heat transfer. [Full article]

Molecular and Biomolecular Electron Transfer Processes: From the Single Molecule to the Cellular Length Scales

Title: Molecular and Biomolecular Electron Transfer Processes: From the Single Molecule to the Cellular Length Scales.
When: Tuesday, May 23, (2017), 12:00.
Place: Departamento de Física Teórica de la Materia Condensada, Facultad Ciencias, Module 5, Seminar Room (5th Floor).
Speaker: Prof. Spiros S. Skourtis, Department of Physics, University of Cyprus, Nicosia Cyprus.

Molecular electron transfer processes are ubiquitous in biology and chemistry and are central to the molecular electronics and energy materials technologies. Biological electron transfer mechanisms are particularly rich, ranging from coherent tunneling to incoherent thermally-activated hopping. I will give a review of recent trends in the theory and simulation of biomolecular electron transfer rates, focusing on the roles of electronic coupling and energy level fluctuations. I will also discuss electron-transport pathway control over length scales that range from the small-molecule to the cellular levels.

More information on IFIMAC Website

Bottom-up Nanoelectronics: Contacting Single Molecules and Nanoparticles
Our research focus is on bottom-up nanoelectronics and in particular the electronic characterization of single molecules and nanoparticles for device applications. For this purpose, we employ several methods to create electrodes, such as direct e-beam patterning, electromigration of Au wires, electroburning of multilayer graphene flakes, (gateable) mechanically-controllable break junctions (MCBJs) and a self-aligned fabrication technique for fabricating nano-spaced electrodes over large lengths. Typical experiments consist of measuring current-voltage characteristics as a function of various external stimuli such as electrode separation, gate voltage, temperature, and/or magnetic field. In this talk, I will discuss experiments on spincrossover nanoparticles and molecules, protein networks, biological nanowires and the use of superconducting electrodes as a new direction to study Shiba states in one-level quantum dot systems.

More information on IFIMAC Website
What does determine the heat flow through a single atom? This is the ultimate question in the field of nanoscale energy transport and its answer is crucial to establish the fundamental laws that should describe the thermal transport in a variety of nanoelectronic devices. In the context of electrical circuits, the atomic scale was first reached with the advent of metallic atomic-size contacts and single-molecule junctions in the 1990s. These systems constitute the ultimate limit of miniaturization and have emerged as an ideal playground to investigate quantum effects related to charge and energy transport. Thus for instance, in recent years it has been shown that transport properties of metallic atomic-size contacts such as the electrical conductance, shot noise, thermopower, or Joule heating are completely dominated by quantum effects, even at room temperature. However, the experimental study of thermal conduction in these atomic-scale systems continues to be a formidable challenge and it has remained elusive to date in spite of its fundamental interest.

This basic open problem has now been resolved in a work published in *Science* by a collaboration between the groups of Pramod Reddy and Edgar Meyhofer (University of Michigan), Fabian Pauly and Peter Nielaba (University of Konstanz), and the IFIMAC researcher Juan Carlos Cuevas. In this work, the authors made use of custom-designed picowatt-resolution calorimetric scanning probes to measure simultaneously the electrical and thermal conductance of gold and platinum atomic contacts all the way down to the single-atom level. This study reveals that the thermal conductance of gold single-atom junctions is quantized at room temperature in units of the universal thermal conductance quantum. It also shows that the Wiedemann-Franz law relating thermal and electrical conductance is satisfied even in single-atom contacts, irrespective of the metal. Furthermore, this work shows that all these observations can be quantitatively explained within the Landauer picture for quantum coherent thermal transport. In particular, this theory clarifies that the observations described above are due to the fact that electrons dominate the thermal conductance in these metallic nanowires, and in the gold case electrons proceed ballistically through the contacts via fully open conduction channels.

The experimental techniques developed in this work will enable systematic studies of thermal transport in atomic chains and molecular junctions, which is key to investigating numerous fundamental issues that have remained inaccessible despite great theoretical interest. [Full article]

Quantized Thermal Transport in Single-Atom Junctions
Radiative heat transfer between closely placed objects is attracting a lot of attention for several reasons. First, recent experiments have finally verified the long-standing prediction that radiative heat transfer can be greatly enhanced over the classical far-field limit set by the Stefan-Boltzmann law for blackbodies if the gap between two objects is smaller than the thermal wavelength, which is of the order of 10 µm at room temperature. This is possible due to the contribution of the near field in the form of evanescent waves (or photon tunneling). Second, this confirmation has triggered the hope that near-field radiative heat transfer could have an impact in different technologies that make use of thermal radiation such as thermophotovoltaics, thermal management, lithography, data storage, and thermal microscopy.

In spite of the progress made in recent years in the understanding of thermal radiation at the nanoscale, several recent experiments exploring the radiative thermal transport in nanometric gaps have seriously questioned this understanding. In particular, measurements on two gold-coated surfaces with gap sizes in the range of 0.2-10 nm have suggested an extraordinarily large near-field enhancement more than 3 orders of magnitude larger than the predictions of fluctuational electrodynamics, which is presently the standard theory used for the description of near-field thermal radiation. A possible solution to this puzzle has now been proposed in a work published in Nature Communications by Víctor Fernández-Hurtado, Johannes Feist, Francisco J. García-Vidal and Juan Carlos Cuevas, Department of Theoretical Condensed Matter Physics and IFIMAC researchers.
Communications by a collaboration between the groups of Pramod Reddy and Edgar Meyhofer (University of Michigan) and IFIMAC researchers Víctor Fernández-Hurtado, Johannes Feist, Francisco J. García-Vidal and Juan Carlos Cuevas. In this work, the authors explore the radiative heat transfer in Ångström- and nanometer-sized gaps between an Au-coated scanning thermal microscopy probe and a planar Au substrate in an ultrahigh vacuum environment. Using the apparent tunneling barrier height as a measure of cleanliness, it was found that upon systematically cleaning via plasma-cleaning or locally pushing the tip into the substrate by a few nanometers, the observed radiative conductances decreased from unexpectedly large values to extremely small ones—below the detection limit of the probe—as expected from computational results obtained within the framework of fluctuational electrodynamics. These results suggest that the huge signal reported in recent experiments might be an artifact due to the presence of contaminants bridging the gap between the tip and the substrate, thus providing an additional path for heat transfer via conduction. Moreover, this work shows that it is possible to avoid the confounding effects of surface contamination and systematically study thermal radiation in Ångström- and nanometer-sized gaps. [Full article]

References

Unexpected Phenomena In The Quantum Transport Through Carbon Nanotubes

Title: Unexpected Phenomena In The Quantum Transport Through Carbon Nanotubes.
Place: Departamento de Física de la Materia Condensada, Facultad Ciencias, Module 3, Seminar Room (5th Floor).
Speaker: Christoph Strunk, Regensburg University, Germany.

Carbon nanotubes have reached a quality that allows for stringent tests of theory. Applying high magnetic fields we perform transport spectroscopy on the first excess electron above the band gap. The observed single particle spectra allow to quantitatively probe the fine structure corrections to the simple Dirac Hamiltonian. The results only superficially agree with expectations based upon accepted models. In particular, we find an unexpected orbital degeneracy of the ground state, and a
mis-match of the orbital magnetic moments extracted from low and high magnetic field regimes.

In addition, the line intensities strongly vary, if the magnetic field shifts the levels across the Dirac cone. This effect can be traced back to deviations from the standard ‘particle in a box’ boundary conditions that apply to the bipartite graphene lattice. The boundary conditions couple the longitudinal and radial parts of the electronic wave functions and drastically affect the transmission amplitude in magnetic field.

Finally, we trace the signatures of the trigonal warping of the Dirac cone at higher energies in the Fabry-Perot-like interference pattern at the highly transmissive hole side of the spectrum. These can be exploited to determine the tube’s chiral angle from transport measurements.

More information on IFIMAC Website

Calculating the Conductance of Single Molecule Junctions from First Principles

When: Friday, 11 September (2015), 12:00h
Place: Departamento de Física Teórica de la Materia Condensada, Facultad Ciencias, Module 5, Seminar Room (5th Floor).
Speaker: Héctor Vázquez, Center Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic.

Abstract:

In this talk I will present the group’s recent work on single molecule transport. Our work uses DFT-NEGF methods to investigate the conducting properties of molecules placed between two metallic electrodes. I will first discuss the importance of linker chemistry and molecular chemical properties on elastic transmission. I will then briefly describe our recent efforts in mapping the different contributions to the inelastic vibrational signal.

More information on IFIMAC Website

The Environment Does the Trick
In a *Nature Nanotechnology News & Views* entitled “The environment does the trick” Juan Carlos Cuevas discusses the recent discovery that single-molecule junctions can behave as diodes with high rectification ratios by exposing different electrode surface areas to an ionic liquid.

In recent years it has been shown that single-molecule junctions can function as some of today’s microelectronics components such as wires, single-electron transistors, and switches, just to mention a few. However, the realization of single-molecule diodes with sufficiently high rectification ratios has remained elusive over the years in spite of the great experimental and theoretical efforts. This situation is particularly perplexing taking into account that the proposal by Arieh Aviram and Mark Ratner in 1974 that a single donor-bridge-acceptor molecule could behave as a diode is often considered as the beginning of the field of Molecular Electronics. Now, Latha Venkataraman and coworkers, based at Columbia University and the University of California, Berkeley, show in an article in *Nature Nanotechnology* that high current rectification at low operating voltages can be achieved in single-molecule junctions by carrying out the experiments in the presence of polar solvents. In particular, the researchers show that by exposing considerably different electrode areas to an ionic medium, junctions with symmetric molecules can behave as single-molecule diodes with rectification ratios that are an order of magnitude higher than previously reported.