RESEARCH PHILOSOPHY & SCHOLAR ACHIEVEMENTS

RESEARCH VISION

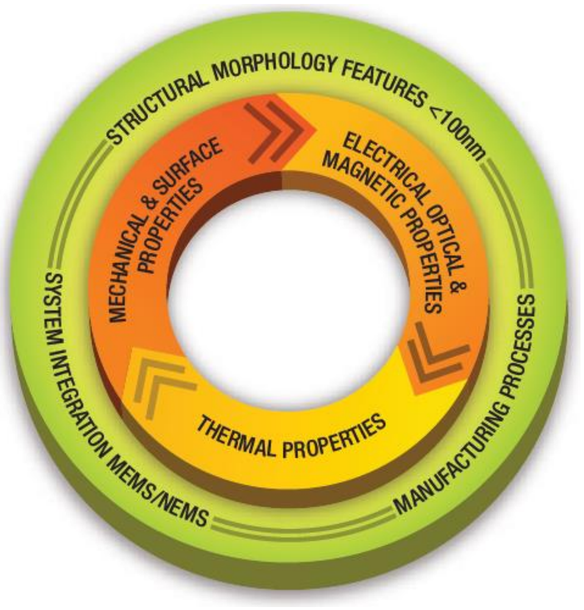


Figure 1 Understanding the interplay between material properties at the Nanoscale, structural features and manufacturing processes in order to properly design low energy system

At the nanoscale, electrical, optical, magnetic, thermal and mechanical properties of materials might be radically different from those in the macroscale. Nanotechnologists strive after the control of such properties for the development of more efficient technologies. Modern nano-materials and devices for example, achieve their impressive performance by relying on clever design and a fine balance of micro- and nano-mechanical properties. Arguably, it is the mechanical properties that are the major single factor determining performance of any material or operation of a device. On the nanometer length scale, yet another very significant physical dimension comes into play - temporal (or “time domain”) behavior of devices or materials. The examples of fast nanoscale physical phenomena range from magnetic or ferroelectric domains switching to lubrication in the hard drive, heat transfer in nanostructures, and functioning of MEMS (Micro-Electro-Mechanical) and NEMS (Nano-Electro-Mechanical) systems. Figure 1 illustrates the need for understanding the interplay between material properties at the nanoscale, structural features and manufacturing processes in order to properly design low energy system. The mission of the research carried out in my group is to provide the background for the successful development of science and technology in the nanoscale with a view to rapid implementation in industry to tackle energy challenges. Future technologies will have to deal with the consequences of confinement and the interactions between the ever decreasing nanoscopic parts composing cutting edge mechanical and electronic devices. Nowadays, efficiency can no longer be understood without the appropriate use of well characterized and functionalized surfaces that provide an intelligent interface between materials and their environment.

SCHOLAR MILESTONES

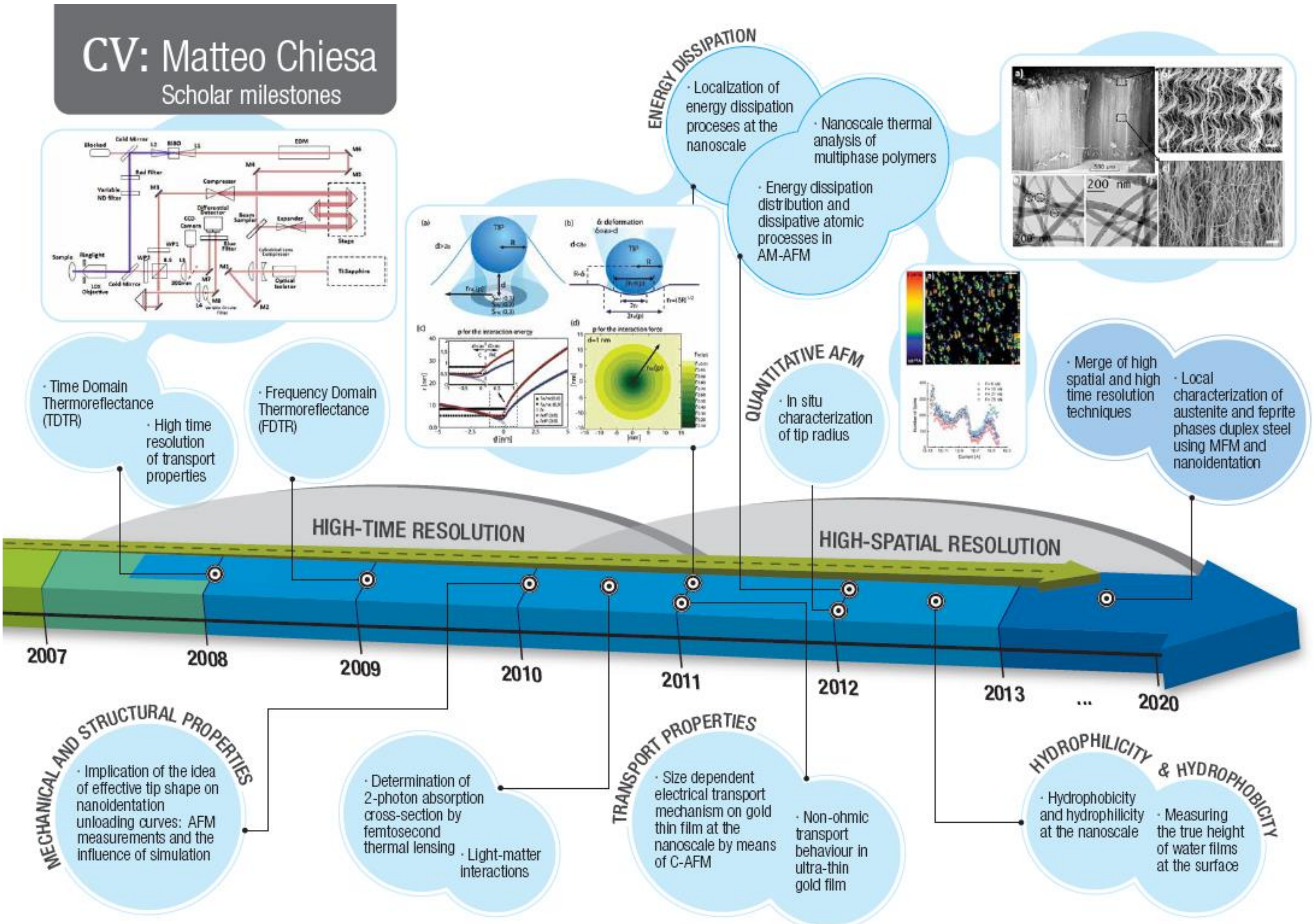


Figure 2 Scholar Milestones

Figure 2 illustrates graphically the scholar milestones and scientific achievements obtained since I have been employed at the Masdar Institute of Science & Technology in September 2007.

At first, I concentrated on the development of characterization techniques for the investigation of thermal transport and mechanical properties over length scales from nanometers upward in solids and liquids. These properties in thin-films and material interfaces play an important role in many technologies such as microelectronics and solid-state energy conversion and when obtained in a reliable way they provide a representation of the quality of thin-film structures something that one can relate to their optical properties. This illustrates the interplay between material properties and structural features at the nanoscale. One of the most reliable ways such measurements are carried out is by means of pump-probe like techniques. This is a two step measurement in which, in the first step, a pulse of modulated light impinges on a sample, depositing energy over a short period of time. The deposited energy causes a change in the sample which can be correlated with a change in its optical properties. In the second step, the "probe" pulse arrives and probes the state of the sample looking at the phase delay of the reflected probe beams in respect to the modulated exciting beam.

The high temporal resolution of the pump-probe technique makes it uniquely suited to the study of a wide range of transport processes occurring on time scales from femtoseconds to nanoseconds and longer. One of the main milestones in developing the characterization tools to study nanostructure was the implement of such experiment that could perform both time and frequency domain investigation of transport properties. We have also developed a variation of this experimental technique to derive mechanical properties of thin films. The novelty of our approach will simplify heavily the characterization of thin film structures opening for the possibility of a simpler benchmark of different materials systems that may be used in thin films applications.

One of the drawbacks of the pump and probe technique discussed above is the modest spatial resolution that hinders the clear understanding of the effect that the structural morphology plays on different properties. Since atomic and nanoscale interactions that govern the macroscopic behavior of materials [1] originate from a length scale that can be accessed using the atomic force microscope AFM [2] I have invested a consistent effort towards mastering AFM techniques with the ambition of merging spatial and temporal resolution. In principle, the versatility of the instrument arises from the fact that single atoms and nanostructures can be probed with a nanoscopic tip and with high precision by monitoring and controlling the structure onto which the tip is mounted; typically a micro-cantilever. In particular, when the cantilever is vibrated, the rich dynamics arising from the non-linear forces have led to the branching of AFM into several modes of operation [4-6]. Nevertheless, a general trend in the AFM community can be identified in the attempt to extend its capabilities towards extracting more quantitative information and increasing sensitivity [7], and throughput [8]. The interest in extracting quantitative information about interaction forces is clearly related to identifying and decoupling chemical, mechanical and other properties that are characteristic of the material. Phase imaging is particularly interesting in dynamic AFM since it provides compositional or chemical contrast with, arguably, the highest resolution [9-10]. Phase contrast was put in firm grounds when Cleveland et al. [11] showed that, through the phase signal, the energy principle provides quantifiable results about the energy dissipated per cycle without putting any restrictions on the nature of dissipative forces. In this way, and while phase imaging was already broadly used in AFM [12-13], it became possible to relate phase shift contrast to variations in dissipation quantitatively. As already predicted by Cleveland et al., different dissipative processes have later been shown to control the dynamics [14]. Some methods to decouple the different dissipative processes have also been proposed where the behavior of amplitude and phase curves is monitored as the cantilever approaches the sample [14-16]. In general, it was shown with relative success that sample parameters can be quantified with the use of force models in combination with experimental data [17-18], sometimes with the use of the energy dissipation principle or even by proposing and increasing the number of experimental observables or constraints [19]. Another way of dealing with energy dissipation is to define effective damping coefficients where these typically involve viscous forces only or, at best, assume that dissipative forces are odd functions of velocity and conservative forces are even [18, 19]. In summary however, while it provides quantitative information, the energy dissipation approach alone is limited in that it does not provide direct information about the unrestricted force distance or magnitude dependencies. In this respect, we have focused on force reconstruction [20, 21] where no restriction is placed in terms of the nature of conservative or dissipative forces, or even on whether the fundamental period of oscillation coincides with the period of the driving force [22, 23]. Two approaches for force recovery have been recently proposed in both the steady and transient states in what we call single cycle measurements [24]. The instantaneous force is accurately reconstructed thus capturing the details of conservative and dissipative interactions. These include a broad range of phenomena from the formation and rupture of bonds to the local detection and probing of water molecules. With single cycle measurements, we add high temporal resolution (possibly microsecond range) to the impressive spatial resolution of AFM, to study kinetic processes moving towards the objective of merging spatial and temporal resolution [24] see Figure 2.

In summary the following contributions deserve to be highlighted:

- **Energy transfer and dissipation at the nanoscale**
  Our work has already led to the development of several methodologies with the capability of characterizing samples with nanoscale lateral resolution and that can provide quantitative information about the state of the sample's surfaces. While there are still some obstacles to be overcome the stage is now set for successful determination of a variety of surface characteristics and processes [24]. Thus, these newly developed techniques will next be used to characterize the functionality of several samples including the surfaces of solar cells and bacteria used for biofuel generation, membrane etc.

- **Tip size quantification and area of interaction**
  In AFM characterizing the tip radius is an experimental prerequisite to elucidate size-properties relationships. A powerful method to characterize the tip radius in situ was proposed [25]. This method will be used in our future investigations to find the dependence of properties and processes on the size of the probe [26].

- **Water affinity at the nanoscale**
  Recent studies have previously shown that hysteretic dissipative interactions can potentially lead to the detecting of the presence of water with nanoscale resolution. We have made a consistent effort in detecting the presence of water with high spatial resolution by:

    - Understanding apparent height [27]
    - Subharmonics excitation [22,23]
    - Energy dissipation methods []
    - Force reconstruction [24]

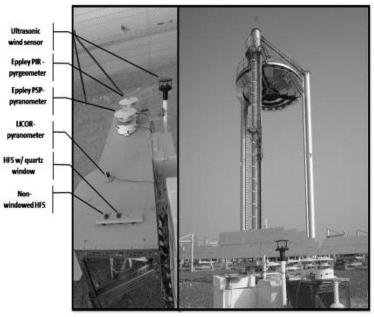
We are currently working towards:

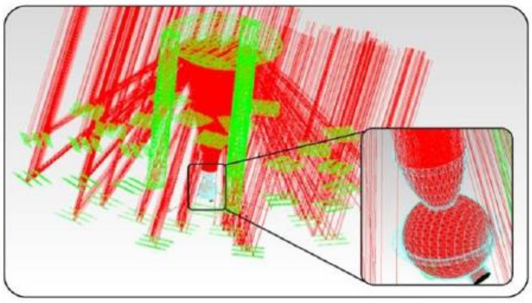
- understanding capillary bridge formation and rupture in the nanoscale and, more generally, dynamic capillary interactions in the nanoscale in the presence of adsorbed water layers
- detecting the presence of water molecules on surfaces with nanoscale or maybe molecular resolution and with the possibility to determine the phase and/or phase transitions, structure, functionality and determine specific interactions
- monitoring the properties of Self Assembled Monolayers (SAMs), or, in general, nanostructures, when these are exposed to moisture in ambient conditions
- the aging process of surfaces and SAMs, or their loss of functionality, when exposed to environmental moisture or otherwise standard conditions

Practical issues
The development and immediate impact of nanoscale science and technology in society depends on being able to understand, control and manipulate matter in the nanoscale where chemical reactions, nucleation processes, corrosion and phase transitions originate. From a practical point of view our projects are essentially based on the effects that atmospheric moisture and the presence of nanoscale water films on surfaces have on such processes. Furthermore, the effects of capillary adhesion might be the problem or the solution of a particular nanoscale project. On one hand, such effects might prove useful in nano-lubrication and might aid in the implementation of damping

mechanisms. On the other hand, these might make the implementation of nanoscale instrumentation and technology such as MEMS and NEMS challenging and/or unachievable, see http://www.lens-online.org/high-spatial-a-time-resolution/67-energy-and-health-sector .

One of the main application where we have actively employed several of the above described characterization tool is the Solar Energy domain. On behalf of Masdar my team has taken up the effort of managing and maintaining the Masdar City Beam Down Facility during the last 4 years see Figure below. My research team was able to tackle many of the technological drawbacks of the design and thanks to the extensive effort invested during the last three years the system will be donated to the Masdar Institute by the current owners. This will have a great boost in establishing a solar research cluster in the UAE, see http://www.lens-online.org/high-spatial-a-time-resolution/68-light-matter-interactions . AFM based techniques have been employed to characterize functionalized surface that can be applied to the heliostats surface in order to reduce the amount of water needed to clean such a surface. Nanoindetation techniques were used to characterize the mechanical properties of the 1D photonic crystals employed in the secondary reflector see picture below. The pump and probe technique was employed to characterize the thermal transport properties of the different mirrors and of the lambertian surface used to characterize the overall performance of the pilot plant.





AFM and Nanoidentation based techniques developed in my group have been employed for the local characterization of ferrite and austenite phases in duplex steel. Duplex steel is the most widely use construction material in desalination plants in the region and thus our interest in this topic, see http://www.lens-online.org/high-spatial-a-time-resolution/69-nanostructures-for-energy-harvesting.

LENS (Leading by infectious passion for science)

In 2008 I convinced a colleague; Dr. Peter Armstrong, to establish the LENS (Laboratory for Energy and Nano Science). The LENS has developed in 4 years in a community of 5 professors from 3 different programs, research staff and students which pursues improvement and enjoyment in their work. The LENS has not had a need for a leader because all of the members have worked harmoniously together towards a common goal continuously defined throughout a contagious process where each other infects his/her own colleagues with his/her passion for scientific achievements. Our critical and inquisitive attitude to each other's research has resulted in a progressive improvement of our skills and a widening of our scientific horizons that has fostered collaboration. This operational mode of our research group has its base in the Scandinavian leadership model and has proven to be successful in the Middle East environment at the Masdar Institute. The LENS has helped and facilitated new coming faculty to establish their research and to develop their research interest and thus it has given an important contribution in developing a collegial environment at the Masdar Institute.

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