Fall 08

Shining light on electrons in low dimensions

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My research focuses on the behavior of electrons (negatively charged particles repelling each other through the Coulomb force) confined in semiconductor crystals. Under special conditions the mutual Coulomb forces among the electrons can create novel emergent states of matter with remarkable properties. In this paper I will emphasize the conceptual framework of this field of research highlighting general phenomena and outstanding issues. The understanding of these novel, highly-correlated electronic states represents an important aspect of nanoscience and it is the basis for the invention of original and innovative practical devices. My research activity aims to achieve this goal.

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1. Introduction

Crystals are solid-state systems in which the constituent atoms are arranged in a regular structure with structural regularity that repeats in space (translational invariance). The atoms in the crystal form chemical bonds and share electrons (see Fig.1, as an example).

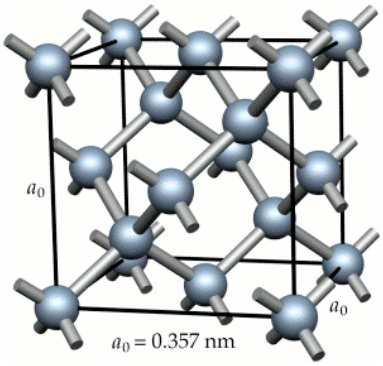

Fig.1 Crystal structure of diamond. Each carbon atom forms covalent bonds to share the four valence electrons (electronic configuration of the carbon atom is $1s^2 2s^2 2p^2$) giving rise to a very rigid structure.

Depending on the nature of the constituent atoms, the electrons can be strongly localized around the atoms or significantly delocalized (mobile). These different configurations give rise to the electrical properties of the crystal and lead to the classification of solid-state materials into metals (such as iron, gold, etc.), semiconductors (silicon or gallium arsenide) or insulators (such as diamond). The study of the properties of the electrons in a crystal was a formidable task in the condensed-matter physics of the 19th and 20th centuries and it has led to remarkable applications such as the transistor (the first transistor based on germanium was invented at Bell labs in 1947, see Fig.2) and to the development of modern electronics.

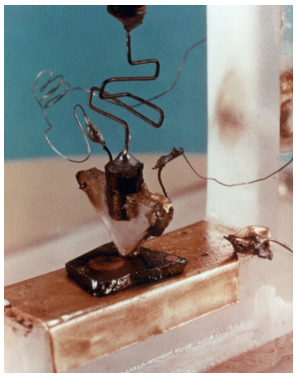

Fig.2 The first transistor. Electron transport between the two ends of a germanium crystal is controlled by point-like (triangular shape) gold contact [1].

The first electronic devices in the fifties had sizes of the order of inches. The quest for miniaturization soon become a driving force for research in solid-state physics. In 1959 Richard Feymann delivered a speech at Caltech [2] entitled "There is Plenty of Room at the Bottom," and the ideas discussed by Feymann therein are now considered at the foundation of nanotechnology. He said:

"*I don't know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements---and by little, I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across. Everybody who has analyzed the logical theory of computers has come to the conclusion that the possibilities of computers are very interesting---if they could be made to be more complicated by several orders of magnitude. If they had millions of times as many elements, they could make judgments. They would have time to calculate what is the best way to make the calculation that they are about to make. They could select the method of analysis which, from their experience, is better than the one that we would give to them. And in many other ways, they would have new qualitative features.*"

He continued:

"*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. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc."*

Miniaturization can not only open the way to novel device architectures and faster computers, but also, more importantly, it offers the opportunity to discover novel phenomena in regimes where the classical laws break down and electrons obey quantum mechanics. In a suggestive paper on the hierarchical structure of science published in *Science* in 1972, Phil Anderson, proposed the concept of emergent states whose properties reflect more than the sum of the constituent parts [3]. One significant example of an emergent state is the superconductor, a metallic system such as aluminum or niobium, where, below a certain temperature, electron resistivity goes to zero. This remarkable phenomenon reveals the existence of a new "emergent" state of matter in which electrons form pairs (the "Cooper" pairs) [4]. The research project I'm going to discuss in the following deals with the experimental realization of these ideas and with the study of emergent states of electrons that are created in low-dimensional semiconductor systems. In our research we study how electrons behave when they are confined to ultra-small regions of space in a semiconductor in which crystal imperfections are virtually absent. This is an important prerequisite to observing phenomena dictated by the quantum-mechanical Coulomb interactions

between electrons (being negative charges, there exists a repulsive force between them that falls off as the inverse of the square of the distance between the electrons). In a conventional bulk semiconductor or in insulating materials there are no electrons free to move in the crystal at low temperatures. In order to create such mobile electrons some of the atoms of the crystal are replaced by special atoms (called the dopants) that can donate electrons that are then free to move (an example of a dopant atom in gallium arsenide or GaAs is silicon). Doping of a bulk crystal therefore creates a three-dimensional gas with a density of (typically) 10^{18} electrons per cm^{-3}. The mobility of these electrons is strongly limited by scattering events with imperfections of the crystal and with the dopant atoms. Despite this, even in a piece of bulk material, most of the electronic properties, particularly at low temperatures, require a massive use of quantum mechanics to be understood. However, when we confine electrons on length scales determined by the De-Broglie wavelength the quantity that defines quantum-mechanically the “extension” of the electron wave-function, the manifestations of quantum mechanics become extraordinary. Typical dimensions that define a nanostructure are of the order of 10nm to 100nm (1nm = 10^{-9} meter). One of the most dramatic consequences of having electrons confined in such small regions of the material is that their motion becomes “quantized”: while in ordinary bulk semiconductors the kinetic energy of the electron can display a continuum of values, in a confined system (or nanostructure), the electron kinetic energy is quantized into well-defined discrete values.

In our studies we work on artificial (man-made) semiconductors in which we are able to confine the electrons in a quasi two-dimensional plane (with “thickness” of the order of 5nm to 10nm) and the scattering events with impurities and imperfections have been almost eliminated. In this way we create what is known as a two-dimensional electron gas or 2DEG. By sophisticated techniques that enable the manipulation of the matter at the nanoscale (those approaches were envisioned by Feymann in 1959 but developed only in the last 10-15 years) we can confine the electrons further in one- or zero-dimensions (zero-dimensional systems are called quantum dots). In a quantum dot, for instance, the electrons are confined in all three dimensions on a semiconducting island with a diameter of around 50nm. In this extreme quantum limit, quantum mechanics is the only language currently available to describe the electron properties.

Most of the research work I’m going to discuss here is about 2DEGs and quantum dots created in artificial GaAs semiconductors. Columbia University has a primary position in this research field thanks to the presence of prominent scientists such as Prof. Horst Stormer (Buckely prize winner in 1984 and Nobel prize winner in 1998 [5]) and Prof. Aron Pinczuk (Buckely prize winner in 1994). Studies of emergent electron states in GaAs nanostructures represent a mature field of research and a number of practical devices (such as high-mobility field effect transistors or infrared lasers) have been developed. Recent developments also pioneered by Columbia researchers together with other groups in Europe have indicated a new material based on carbon (called graphene) as a perfect realization of a two-dimensional layer of electrons only one-atom thick (less than

1nm) [6]. The appearance of graphene on the scene in 2004-05 represented a breakthrough in nanoscience, and the most innovative part of my research work at the Italian Academy has to do with the experimental investigation of this novel system. One of the key advantages of graphene is that it can be fabricated with a simple approach starting from pieces of natural graphite that cost less than a dollar. In contrast, the growth of artificial semiconductor crystals based on GaAs requires running very expensive equipment. This paper is structured as follows: in Chapter 2 I'll briefly describe the techniques used to make gallium arsenide artificial structures, 2DEGs and nanostructures. In Chapter 3 I'll review a few properties of electrons confined in nanostructures, and in Chapter 4 I'll explain the experimental approach that we use in the investigation of electrons in low dimensional systems. Finally in Chapter 5 I'll present the planned research activity on graphene.

2. How do we make semiconductors nanostructures with confined electrons

As mentioned above a 2DEG is a gas of electrons with typical densities of 10^{11} cm^{-2} that are free to move in two dimensions, but tightly confined in the third. This tight confinement leads to quantized energy levels for motion in that direction. Thus the electrons appear to be a 2D sheet embedded in a 3D world. Such a system is currently realized in artificial (man-made) semiconductor structures based on different types of materials. The best material in terms of the mobility properties of the electrons is based on gallium arsenide GaAs and aluminum gallium arsenide AlGaAs. The diagram in Fig.3 left panel shows a cross-section through a wafer consisting of layers of GaAs and AlGaAs. The wafer is grown by Molecular Beam Epitaxy (MBE) [7], which produces near-perfect crystalline layers of extreme purity, with nearly atomically sharp transitions between layers. To the left is shown the corresponding band diagram, i.e. the energy of the conduction band (the lowest kinetic energy that mobile electrons can have). The dashed line is the Fermi energy (roughly defined as the highest energy that electrons have in equilibrium). The conduction bands of GaAs and AlGaAs are offset from each other, and this allows electron to collect in the GaAs but not in the AlGaAs. To provide the electrons, silicon doping is included in the middle of the AlGaAs region (shown in red). These donors become positively ionized and provide electrons, which collect in the neighboring GaAs, though they cannot go too far away because they are attracted back to the positive ions. Thus the resulting electric field created between the positive ions and the negative electrons distort the conduction band into the shape shown, where there is a triangular "well" at the interface, and this goes slightly below the Fermi energy so that electrons can collect there. This well is so narrow that all the electrons there behave as quantum-mechanical waves, with the same wavefunction in the vertical direction. Thus the only degrees of freedom for the electrons are in the plane of the interface, and so they are effectively in a two-dimensional world. It must be stressed that mobile electrons in the crystal environment are characterized by a charge –e and by an effective mass which is only a fraction of the electron mass in vacuum. The effective mass is an elegant way to

incorporate the complex pattern of interactions of the electrons with the crystal into a single parameter. When this is possible, our gas of electrons moving in the complex environment of a semiconductor crystal can be mapped into a gas of virtually free electrons with the effective mass and a renormalized Coulomb interaction.

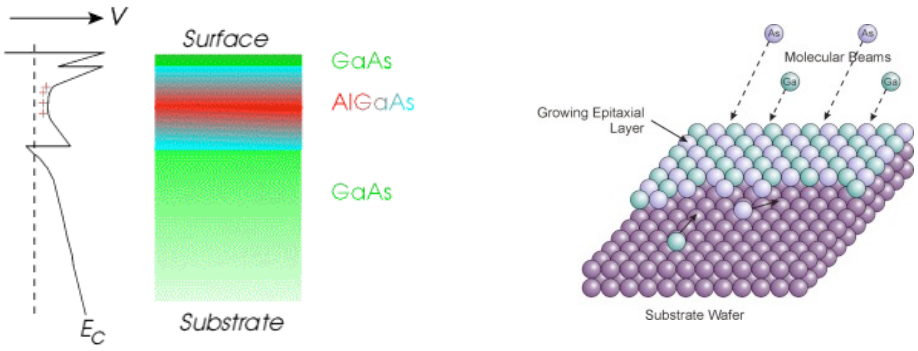

Fig.3 Left: Sequence of semiconductor layers along the growth direction in a typical semiconductor heterostructure. Si donor atoms (+ sign in the figure) are inserted in the AlGaAs layers and provide electrons to the semiconductor. Electrons fall in the minimum of the energy profile (with triangular shape) and remain trapped in this minimum. They are free to move in the perpendicular plane. Right: schematics of the MBE growth process of GaAs.

Further confinement in the plane can be achieved by modern techniques of e-beam nanolithograpy and chemical etching (the so-called top-down nanotechnology approaches) that are able to manipulate the matter up to a resolution of 10-20 nm. Examples of nanostructures obtained by these methods are shown in Fig.4.

3. Main properties of electrons in nanostructures and applications

More than one century ago, Hall showed that when the electron gas in a metal is placed in a magnetic field B, an electrical (transverse) resistivity develops for the electron motion in the direction perpendicular to the applied voltage (or electric field, see Fig.5). The essence of this effect is due to the fact that electrons while moving along the applied electric field start making circular orbits perpendicular to the magnetic field (the reason is the existence of the Lorentz force that is directed perpendicular to both the magnetic field and electron velocity). This produces a displacement of electrons perpendicular to the direction of the applied electric field. This transverse or Hall resistance displays a linear behavior in the values of B with a proportionality constant given by the inverse of the electron charge times the density *n* and the velocity of light c: $R_H = B/nec$.

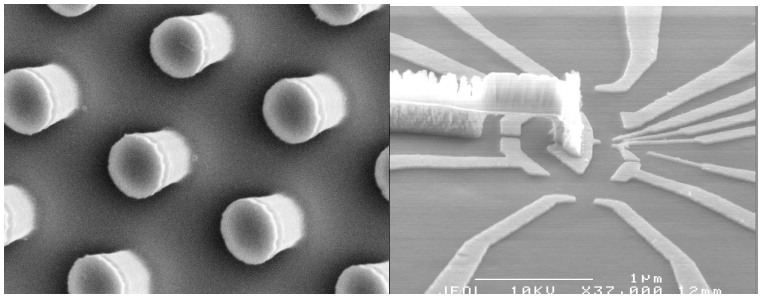

Fig.4 Left: scanning electron microscope (SEM) image of quantum dots that are realized by etching away the semiconductor material around metallic disks that are deposited on top of the semiconductor. This process produces vertical pillars with a diameter of 200nm. Electrons are trapped inside these pillars and there are significantly affected by Coulomb forces [8]. This produces peculiar arrangement of electrons in the nanostructure. The number of electrons inside a QD can be controlled with single-electron accuracy. Right: SEM image of a nanoelectronic device obtained by depositing metallic gates on top of the heterostructure containing a 2DEG. By polarizing the gates with a voltage bias, the electrons are removed from underneath the gates. This defines nanometer-scale channels and electrons are forced to move only within these channels [9].

The Hall effect is nowadays used to measure the electron density in metals and semiconductors with great accuracy.

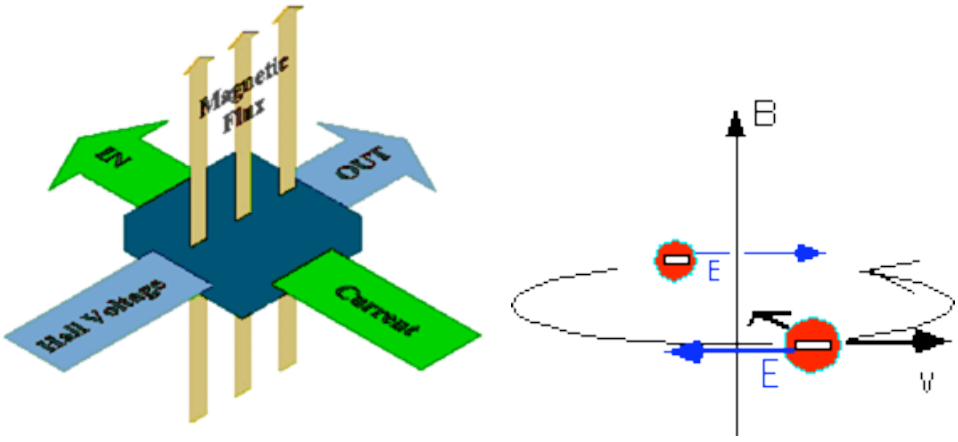

Fig.5 The classical Hall effect. Left: when electrons move in one direction under the action of an applied electric field (green arrow), an electric field in the perpendicular direction (the Hall voltage) develops in the presence of a magnetic field. This effect is due to the circular motion of the electrons in the plane perpendicular to the magnetic field induced by the Lorentz force (right panel). The Hall resistance is the Hall voltage divided by the current.

The Hall effect is valid in 3D as well as in 2D systems. In 1978, however, the german physicist Klaus Von Klitzing discovered a marked deviation from this linear behavior in magnetic field working on 2DEGs confined in Si-based heterostructures and at low temperatures of the order of 1K [10,11]. This

surprising behavior is shown in Fig.6. The Hall resistance becomes quantized at some magic values of the magnetic field. At the same values, the transport of electrons along the applied electric field becomes dissipationless (i.e. the longitudinal resistance goes to zero!). This quantum version of the Hall effect originates from the quantization of the orbital motion of the electrons into specific values of the energy called Landau levels (i.e. the frequency of rotation of the electrons assumes only well-defined values). Each time the electrons occupy an integer number of Landau levels (and that occurs by varying the magnetic field at a fixed electron density or by varying the density at a fixed magnetic field), the quantum Hall effect (QHE) occurs. In 1982 Horst Stormer, Daniel Tsui and Art Gossard, discovered a similar effect in ultra high mobility 2DEGs in GaAs/AlGaAs heterostructures occurring at fractional occupation (1/3) of one Landau level at temperatures below 1K [12,5]. Robert Laughlin showed in 1983 that the fractional quantum Hall effect was the consequence of the formation of a new emergent 2D quantum liquid of electrons induced by Coulomb interactions [13,5]. In this quantum liquid the fundamental charge excitations are peculiar particles having a fraction of the total electron charge. Current experiments at temperatures as low as few mKs have revealed the existence of an extraordinary rich family of 2D quantum liquids associated with a hierarchical sequence of fractional values of the filling factor.

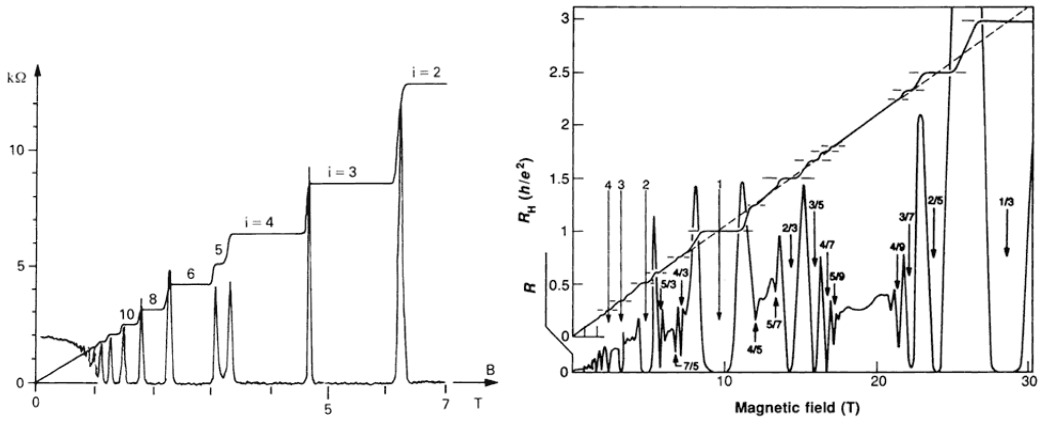

Fig.6 The quantum Hall effect: The integer quantum Hall effect (on the left) and the fractional quantum Hall effect (on the right). The figures report the measured resistances as a function of the magnetic field at temperatures below 1K.

Other examples of correlated states occur when Coulomb interactions become even stronger as the electrons are forced to stay closer (for instance in a quantum dot). In QDs states of correlated electrons can emerge that show molecular-like behavior. In such electron molecules the electrons localize at specific positions in space and excitations of the electrons correspond to vibrations around their equilibrium positions. As we will see below, these vibrations can be probed using optical laser beams [14] (Fig.7 shows a cartoon of vibrational excitations in a QD with four electrons). Wigner was the first to predict in 1934 the formation of such states at sufficiently low electron density and

temperatures [15]. Their observation represents a challenge of current research at the frontiers of nanoscience.

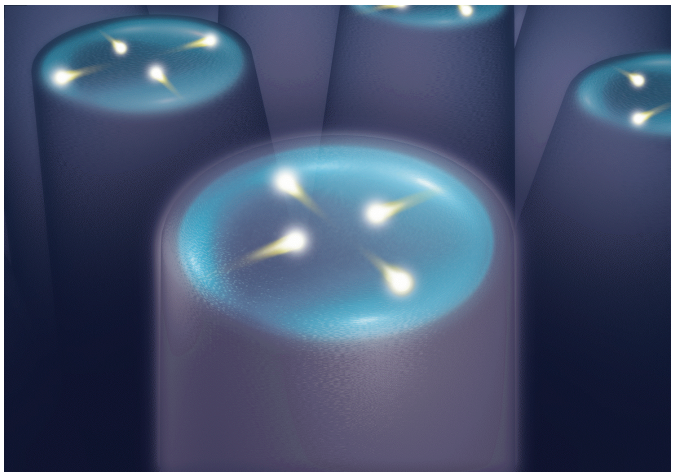

Fig. 7 Cartoon showing one particular mode of vibrations of four electrons (white circles) in quantum dots. These collective modes of vibration can be excited by photons that interact with the QD at particular frequencies.

The quantum confinement of electrons in a QD has another remarkable manifestation in the electrical transport. Experiments can measure the electrical conductance of a device made by two source and drain metallic contacts connected by tunnel junctions to a QD (Fig.8) [16].

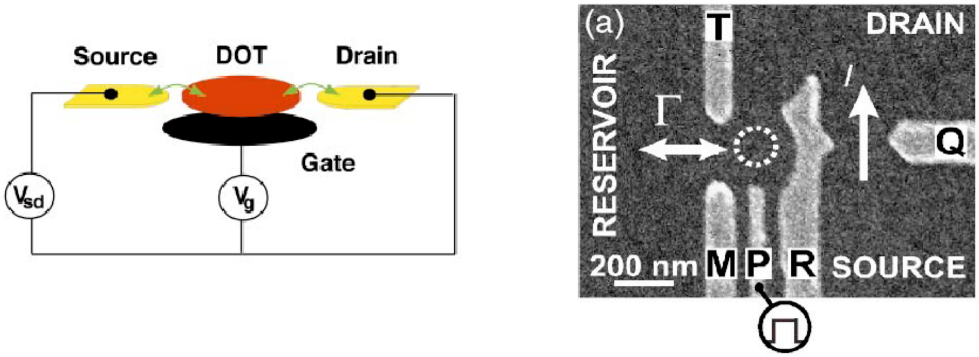

Fig.8 Left: Schematic picture of the QD device used to observe Coulomb blockade. Right: Scanning electron microscope image of a QD device (dotted circle with diameter of around 100nm) defined by e-beam nanolithography.

Due to the discreteness of the electrical charge, current flow through a tunnel junction is a series of events in which exactly one electron passes through the tunnel barrier. Every time this happens, the QD is charged of one elementary charge by the tunneling electron, and when another electron is injected into the QD, this requires a voltage build-up of $U = e / C$ where e is the elementary charge of the electron (1.6×10^{-19} coulomb) and C the capacitance of the QD. The required energy e•U is needed to win the repulsive interaction between two

electrons when they stay close in the same region of space. If the capacitance is very small, and that happens in a QD, the voltage buildup can be large enough to be experimentally observed. The electrical current from the source metal to the drain metal through the QD is then suppressed unless the voltage U is applied. The resulting conductance of the device shows a series of peak each of them associated to the addition of one electron to the QD island (see Fig.9). This effect is called Coulomb blockade.
In order for the Coulomb blockade to be observable, the temperature has to be low enough so that the characteristic charging energy (the energy that is required to charge the junction with one elementary charge) is larger than the thermal energy. For capacitances above 1 femtofarad (10^{-15} farad), this implies that the temperature has to be below 1 kelvin. This temperature range is routinely reached in dilution refrigerators (see below). An additional property of electrons filling the QD island is that the rule that determines the successive filling of the QD quantized energy levels is similar to that that applies to atoms [17]. For this reasons the semiconductor quantum dots are also called artificial atoms.

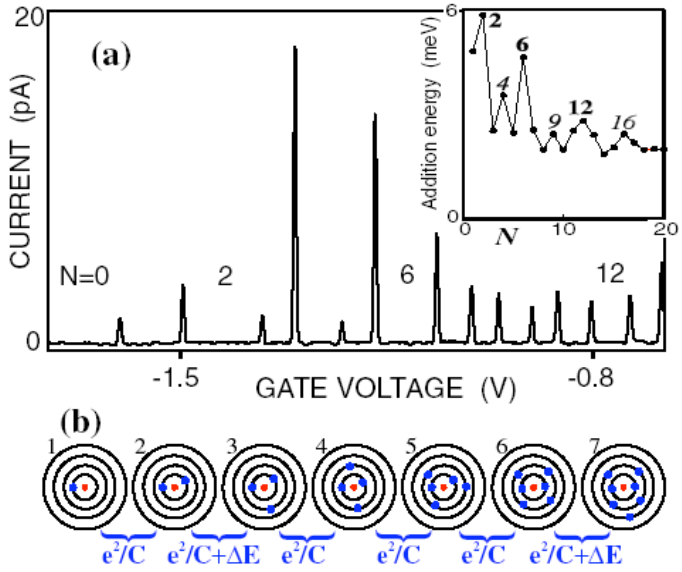

Fig.9 Measurement of the current through a quantum dot as a function of a gate voltage that is used to change the number of electrons (N) in the QD. A sequence of peaks are visible and originate from the Coulomb blockade effect. The Coulomb blockade energy depends on the number of electrons in a way that can be understood by a simple model of the QD energy levels based on the atomic-like shell structure (bottom part).

How do we probe electrons at the nanoscale

In our studies of the correlated electron states in nanostructures we use the experimental technique of inelastic light scattering [18]. This is a method that allows probing the elementary excitations of the quantum liquid of electrons by simply shining light on the system and collecting the scattered photons. The

process involves interaction of photons with the elementary electronic excitations. Under particular conditions some photons give part of their energy to the electronic system and excite the collective modes (what happens is similar to the case of a stone throw into the water. The kinetic energy of the stone is transferred to the liquid, which reacts by making waves). In the 2D case these excitations can be viewed as collective electronic waves moving into the quantum liquid similar to the case of ordinary waves in a conventional liquid. In quantum dots, the electronic excitations can represent the vibrations of the few confined electrons out of their equilibrium positions. From a conceptual point of view a mechanism for light scattering processes is represented in time-dependent perturbation theory by third-order processes in which the incoming photon at energy ω_L creates an intermediate valence-to-conduction band (or inter-band) electron-hole state (an electron absorbs the energy of the photon and acquires a different kinetic energy. Since electron kinetic energies are described in a semiconductor by energy versus wavevector dispersion relations or energy bands that process is called inter-band transition). This state then relaxes to a lower-energy inter-band state by creation or annihilation of the collective excitation of the electron system. In the third step there is creation of the scattered photon at ω_S.

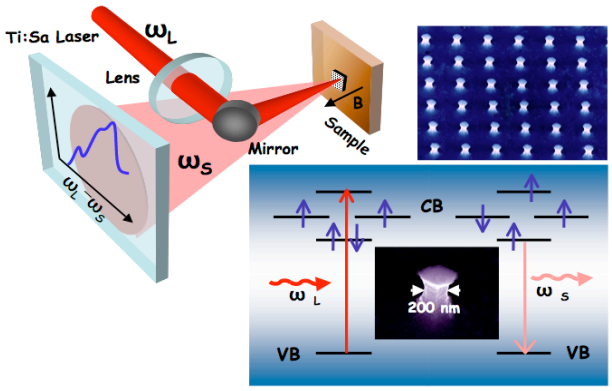

Fig.10 The setup in the back-scattering geometry is shown on the left. Scanning Electron Microscope images are shown for an array of QDs and for a single QD. A scheme of the experiment is shown in the bottom right. An incident photon at ω_L resonating with a transition close to the gap between conduction (CB) and valence (VB) bands is absorbed creating an electron-hole pair and a scattered photon at ω_S is emitted with annihilation of a different electron-hole pair, leaving an excitation of energy $\omega_L - \omega_S$. The electronic configurations depicted correspond to the case of four electrons that occupy the quantized energy levels of the QD.

In resonant light scattering experiments, a finely tunable Ti-Sapphire laser is used to generate the incident photon while the scattered photon is

spectroscopically resolved by a triple monochromator which allows to detect the intensity of the scattered radiation as a function of the energy difference $\omega_L - \omega_S$ (Fig.10 describes as an example the set-up used for the investigation of QDs). In order to avoid heating of the electrons, the incident light intensity is kept below 10^{-4} W/cm^2. The experiments are performed in a dilution fridge with an optical access. The dilution fridge is need to keep sample's temperature below 1K.

The dilution fridge (the main unit is shown in Fig.11) exploits the fact that when a mixture of the two isotopes of helium is cooled below a critical temperature, it separates into two phases.

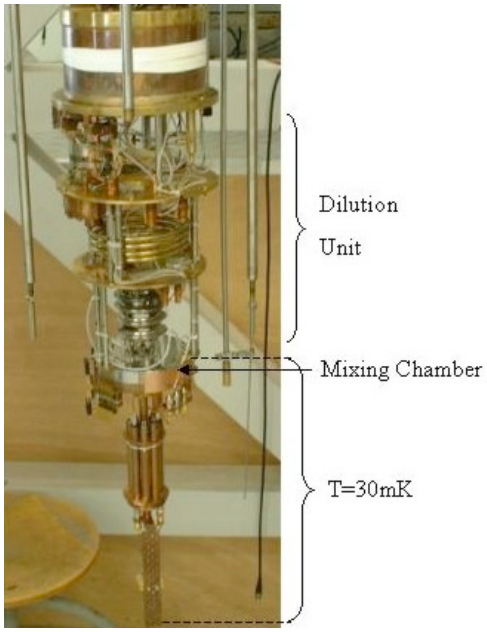

Fig.11. The image shows a typical dilution unit. The fridge is inserted in a dewar that has multiple chambers filled with liquid helium (4.2K) and liquid nitrogen (77K) to prevent heating from room temperature. A magnet is often included to provide a magnetic field. Typical magnets exploit superconducting wires and need to be fully immersed in liquid helium during operation.

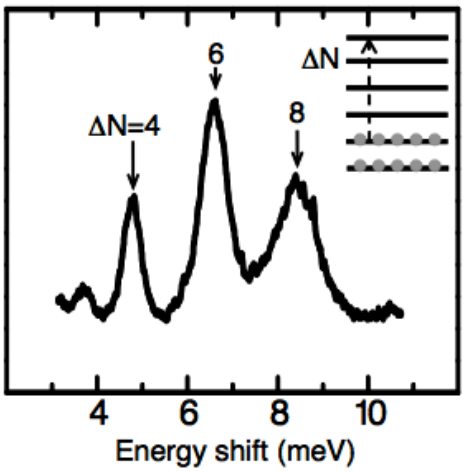

Fig.12 Inelastic light scattering spectrum in a QD at a temperature of 2K. The figure reports the scattered photon intensity as a function of the energy difference between the incoming photon energy and the scattered photon energy. The peaks represent electronic transition across the quantized energy levels of the QD.

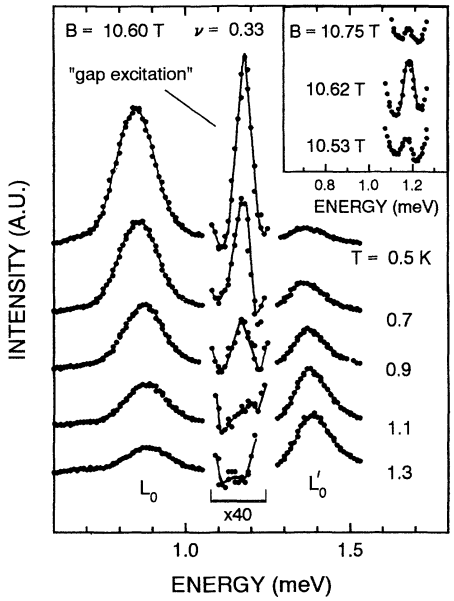

Fig.13 Inelastic light scattering observation of the collective excitations (gap excitations) of the quantum liquid of electrons in the fractional quantum Hall effect. The correlated liquid exists only at temperatures below 1K. The energy of the mode is at 1.2meV. The other two peaks visible in the figure originate from inter-band optical recombination (luminescence) of electron-hole pairs [20].

The lighter "concentrated phase" is rich in ^{3}He and the heavier "dilute phase" is rich in ^{4}He. Since the enthalpies of the ^{3}He in the two phases are different, it is possible to obtain cooling by "evaporating" the ^{3}He from the concentrated phase into the dilute phase. In a gross simplification, the concentrated phase of the mixture is pretty much liquid ^{3}He, and the dilute phase is effectively ^{3}He gas. The ^{4}He composing the bulk of the dilute phase is inert and noninteracting, and may be neglected. The evaporation of ^{3}He from the "liquid" phase to the "gas" phase cools the sample. During continuous operation, the ^{3}He must be extracted from the dilute phase (to prevent saturation) and resupplied to the concentrated phase. During the operation of the fridge, the mixture continuously circulates through the complex heat exchangers. The phase separation takes place at the lowest part, which is called the *Mixing Chamber*.

This is the very heart of the fridge, its coldest part. The sample which is to be cooled is thermally anchored to the Mixing Chamber by a copper piece. External pumps are used to put He into motion.
Figures 12 and 13 shows typical inelastic light scattering spectra obtained in a 2DEG in the quantum Hall regime and in a quantum dot with four electrons. Figure 12, in particular, shows a sequence of peaks that represent consecutive electronic excitations among the quantized energy levels of QDs similar to those shown in Fig.4 (left) [19]. The impact of quantum mechanics here is clearly visible in the discreetness of the scattered light signal. Figure 13 reports the first observation of the collective mode of electrons in the emergent fractional

quantum Hall liquid (fractional occupation of the lowest-energy Landau level equal to 1/3) [20]. The observation exploits the inelastic light scattering technique. The peak at 1.2meV is associated to a large scattering of photons due to creation of the collective mode in the quantum liquid.

5. Graphene

As said at the beginning, recent research activities by groups in Europe and at Columbia University have shown that it is possible to deposit single layers of graphite (thickness of 0.2nm) onto a substrate (typically silicon with silicon dioxide on top). It is also possible to see them by a conventional microscope (see Fig.14 left and middle panels) and furthermore it is possible to induce into graphene a 2DEG and control its electron density by metallic gates. This single atomic layer of graphite consists of a single layer of carbon atoms that are arranged in a honeycomb lattice (Fig.14 right panel).

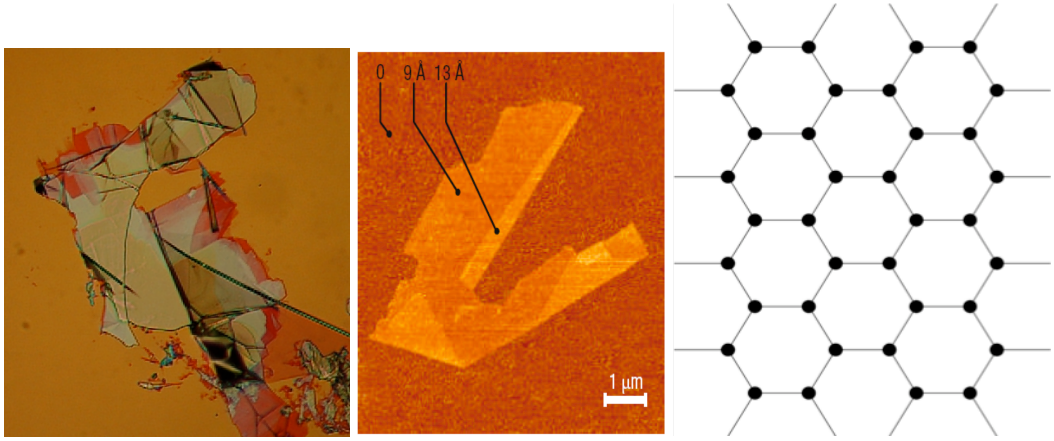

Fig.14 Optical microscope images of graphite flakes left on top of silicon/silicon dioxide substrate by the scotch tape method. First the scotch tape is used to exfoliate the flakes from a piece of natural graphite. Then the same scotch tape is pressed on the substrate to transfer the flakes from the tape to the substrate. The middle panel shows single a few-layers graphene. The right panel displays the honeycomb arrangement of the carbon atom (solid circles) in graphene.

While used as an example in theoretical studies of a system in the extreme 2D limit [21], graphene has recently captured a great interest because of the demonstration that relatively large flakes of monolayer and multilayer graphene displaying unique quantum transport properties (a monolayer graphene displays the quantum Hall effect) can be made by a very simple inexpensive micromechanical cleavage method using a scotch tape and a piece of natural graphite [6,22,23,24]. The unique electronic properties manifest the peculiar band structure of graphene: conduction and valence bands touch at two inequivalent points at the corners of the Brillouin zone and around those two points (called Dirac points) the energy dispersion relation (Energy versus wavevector) is linear and the electron dynamics appears thus “relativistic” (electrons have zero effective mass) with a velocity of 10^6 m/sec, 300 times

slower than the speed of light [6]. The implications of those properties on the magneto-transport behavior are remarkable: high mobility graphene samples exhibit an unusual sequence of quantum Hall (QH) effects [22,23,25] and more recently a collaboration led by people at Columbia University has shown the impact of valley and spin degree of freedoms on the Landau level structure of graphene at ultra-high magnetic fields [26].

Like fermions in the Dirac equation, the quasiparticles in graphene display a particle-hole symmetry that results from the symmetry of the band structure at the zero gap state. The zero gap of graphene is remarkably at work in the ambipolar electric-field-effect (EFE) seen in graphene flakes. The EFE enables the continuous tunability of the charge density between electrons and holes at densities reaching 10^{13} cm^{-2} [6]. The EFE in graphene has created the venues to explore fundamental behaviors such as the unconventional quantum Hall effect mentioned above that can now be observed at room temperature [25]. Particle-hole symmetry of Dirac fermions in graphene is also shown by measurements of electron-phonon coupling by Raman scattering experiments [27, 28]. These inelastic light scattering experiments can determine the frequencies of vibrations of the carbon atoms (there are two main vibrations of the graphene lattice called g and d' modes that couple to light) and are very sensitive on the number of graphene layers as shown in Fig.15.

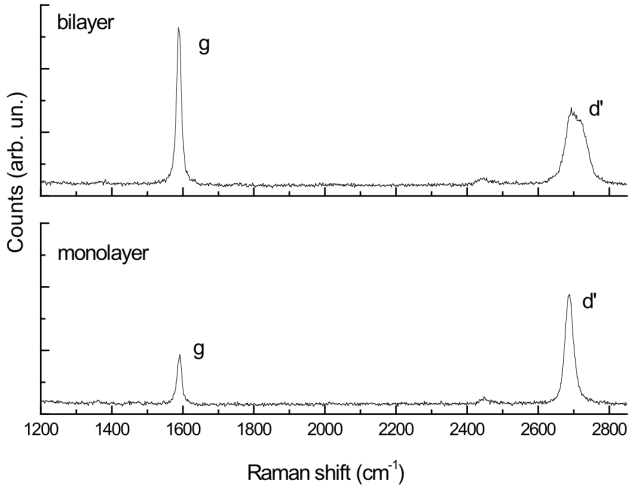

Fig.15 Inelastic light scattering from vibrational modes (Raman spectra) in single layer and bilayer graphene. Spectra are taken at room temperature.

Graphene is an alluring candidate for the age that will follow the silicon age in contemporary electronics. Graphene can withstand currents as large as 10^8 A/cm^2. While at room temperature silicon has a mean free path of 0.01 μm (the average distance between the electron gets scattered by imperfection of the crystal), graphene has a mean free path of about 0.3 μm. This striking property of graphene creates the tantalizing possibility of submicron devices operating in ballistic limits at room temperature [29]. While graphene flakes obtained by micromechanical cleavage may remain unsurpassed for fundamental physics

studies, applications in electronics require the capabilities to fabricate wafers supporting atomic layers of graphene suitable for industrial processing. There has been progress in fabrication of atomic layers of graphene on silicon- and carbon-terminated faces of silicon carbide [30, 31]. Recent studies on such epitaxial layers of graphene have revealed band structure effects [32], cyclotron resonance probed by far-infrared optical absorption experiments [33] and Dirac fermion quasiparticle effects [34]. However, the absence of quantum Hall signatures in the epitaxial layers indicate that much remains to be done to achieve superior quality wafers of epitaxial graphene.

In my research activities I'll carry out fundamental research on the physics of graphene at high magnetic fields, and will try to exploit this knowledge to develop graphene-based nano-electronic and bio-electronic devices. This material system is offering promising novel routes for developing sub-micron electronic devices that may display robust quantum-mechanical effects up to room temperature. In addition, graphene is emerging as an elegant laboratory to test fundamental phenomena related to electron-electron and electron-crystal lattice interactions at the nanoscale. Research in graphene is still at its infancy and reaching a better understanding of its electronic properties and developing optimized techniques for its production could open the venue for a pervasive use of graphene in future information technology.

The Nanocenter at Columbia University will provide a base for all of the work that I propose to carry out during the duration of the fellowship. During the research activity I plan to collaborate with several people of the NSEC at Columbia University that are at the forefront of the research on graphene and will provide the best scientific environment to reach the proposed research objectives in the limited period of one academy semester. At the same time I propose to use this fellowship to set-up a long-term collaboration between my group at the NEST (National Enterprise of Nanoscience and Nanotechnology) center of Scuola Normale Superiore in Pisa (Italy) and people at the NSEC center of Columbia University. Initial work on graphene at NEST is centered on fabrication of graphene layers by epitaxial methods and the exploration of the structural, optical and electrical properties of the fabricated layers.

The proposed project will be centered on the application of inelastic light scattering techniques pioneered by Columbia professor Aron Pinczuk to study the electronic (inter-Landau-level) spin and charge excitations of graphene 2D electron-hole systems in EFE devices under the application of quantizing magnetic fields. The goal will be to unravel the collective modes of the quantum Hall states, identify states with ferromagnetic order and to evaluate the impact of fundamental electron-electron interactions in the 2D electron and hole fluids that emerge in graphene at high magnetic fields. I recall here that low-lying neutral excitations of quantum Hall liquids in conventional semiconductor heterostructures have been extensively studied by inelastic light scattering by many groups [20,35]. The application of this technique to graphene is challenging but it can lead to a significant understanding of the graphene charge and spin

states and will offer new experimental results to test the conceptual theoretical framework proposed for the case of graphene quantum Hall ferromagnets [36]. It must be stressed that transitions between graphene Landau levels in the presence of magnetic fields has been probed so far by infrared spectroscopy only. The Kim and Stormer groups at Columbia University in collaboration with the National High Magnetic Field Laboratory group in Tallahassee, Florida have employed this technique to study Landau level transitions in micromechanical graphene [37].

In addition I would like to exploit this fellowship to further develop the technique for growing graphene using epitaxial methods initially from SiC substrates and then eventually exploring other substrates such as boron nitride, a polymorph displaying an honeycomb crystal structure similar to graphene. The optical, electrical and transport properties of these graphene samples will be tested in collaboration with the groups above mentioned at Columbia University. Finally, graphene samples would represent ideal candidate to develop biosensors. Indeed thanks to the unique close proximity of the 2D electrons/holes to the surface, its transport and optical properties are expected to be significantly affected by the adsorption of molecules (see Fig.16) or biomolecules such as proteins or DNA.

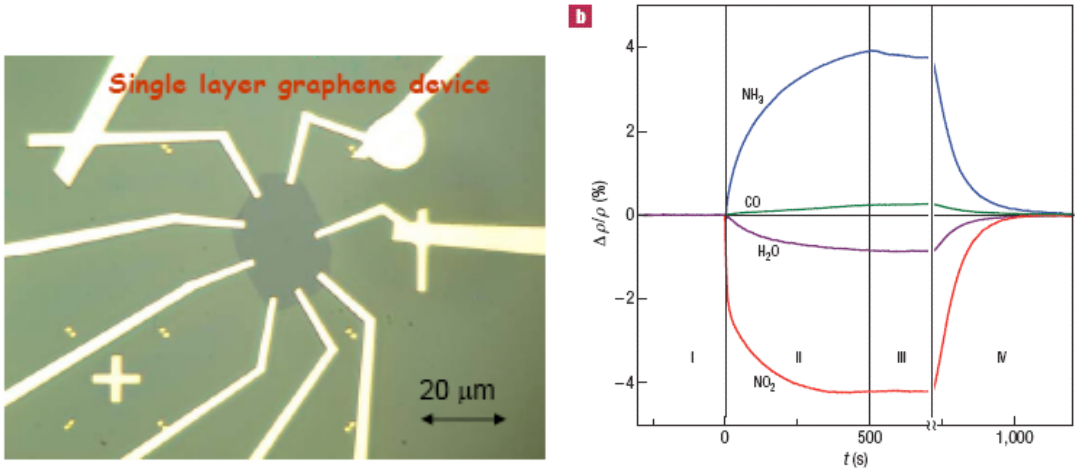

Fig.16 Optical image of a graphene electronic devices. Gold/titanium metallic fingers are used to apply voltages and measure the electronic resistivity. Right panel shows examples of the evolution in time of the resistivity when different types of molecules are added in the environment surrounding the device. t=0 signals when the molecule are added with a given concentration. Molecules attach at the graphene surface and modify the electrical resistivity.

I plan to explore this particular application by studying graphene samples functionalized with simple (bio)molecules (including DNA) i.e. monitoring the change of the principal vibration bands of graphene by Raman spectroscopy and monitoring the modification of electronic conduction in EFE devices.

6. Conclusions

In this paper I have offered a bird-eye view of the tantalizing possibilities offered by nanotechnology and nanoscience and I offered a glimpse of the research activity I'm doing in this field with my group and of the research project that I'll carry out at Columbia during this semester.

With this presentation I tried to highlight one of paradox of this modern branch of condensed-matter science: As we go smaller, we find many more opportunities to discovery novel emerging phenomena and to develop innovative device architectures for practical applications. It is remarkable that the paradox was already pointed out 50 years ago by Feymann with his statement "there is plenty of room at the bottom". In his speech he also mentioned the ultimate limit of nanotechnology, which is the manipulation of single atoms (sub-nanometer scale). At the beginning of the third millennium, we are at the stage where atoms can indeed be moved on a substrate and studied with great accuracy. By using sophisticated microscopes called scanning tunneling microscopes or STMs [38], researchers can arrange atoms to form desiderate structures.

Figure 17 shows a representative example of iron atoms positioned on a metallic substrat to form a stadium-like structure in order to "corral" some electrons and force them into "quantum" states of the elliptical structure [39].

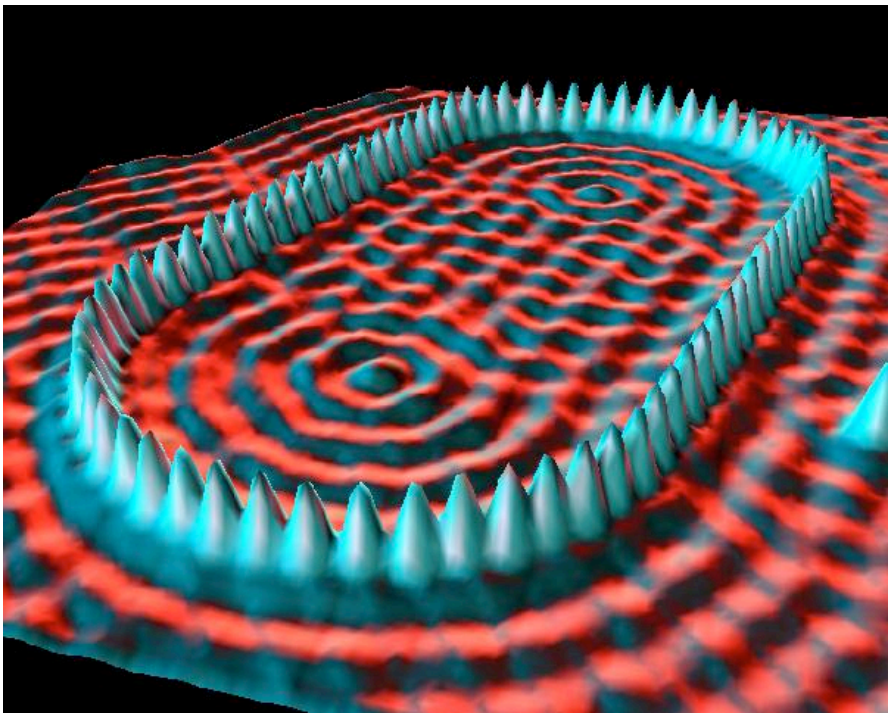

Fig.17. The quantum corral made by iron atoms deposited on a metallic surface. Each atom (a peak) has a width of a fraction of a nanometer. The ripples originate from the interference of the electronic wavefunctions of the electrons that are trapped into the stadium-like structure.

The ripples in the ring of atoms are the density distribution of a particular set of quantum states of the corral. As the figure shows, it is not only possible to manipulate single atoms but also to image them with a precision that was considered inaccessible at the time of the Feymann's famous speech. This emerging single-atom nanotechnology and nanoscience represents with graphene one the most intriguing fields at the frontiers of current research.

Nanoscience is a mature field of research. Despite this I believe that the gold-age of nanotechnology and nanoscience is still in front of us. It is of course difficult to predict what will come next. Maybe quantum computers will be available on our office desks in the next years. Perhaps quantum teleportation will become possible. Hopefully it will be possible to develop smart nanodevices able to monitor cellular activities in our body in real time and deliver pharmacological molecules to selected parts of the cell as soon as a pathological disease starts developing. More is expected to come from the cross-fertilization of ideas and techniques between physics and biology. On top of all of those possible avenues of research I'm sure that we will continue to discover novel unexpected emergent states of matter whose properties will reflect more than the sum of their constituent parts. It is indeed this peculiar characteristic of the matter at the nanoscale that makes the research in this field a fascinating voyager of incredible intellectual value.

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